PEDIATRIC CLINICS OF NORTH AMERICA

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CONTENTS

SYMPOSIUM ON CARDIOVASCULAR DISEASES

page 1 **Willis J. Potts, M.D.**
Stanley Gibson, M.D.
Foreword

3 **Stanley Gibson, M.D.**
Eyes, Hands and Ears in the Diagnosis of Heart Disease in Children

13 **Jesse E. Edwards, M.D.**
Functional Pathology of Congenital Cardiac Disease

51 **Robert A. Miller, M.D.**
The Electrocardiogram in Congenital Malformations of the Heart

73 **John D. Keith, M.D.**
Angiocardiography in Infants and Children

93 **Robert F. Ziegler, M.D.**
Clinical Cardiac Catheterization in Infants and Children

115 **James W. DuShane, M.D.**
Diagnosis of Congenital Cardiovascular Malformations Unaccompanied by Cyanosis

131 **Benjamin M. Gasul, M.D.**
Carl J. Marienfeld, M.D.
Clinical Diagnosis of the Cyanotic Types of Congenital Malformations of the Heart

147 **William O. McQuiston, M.D.**
Anesthesia for Cardiac Surgery in Children

159 **Willis J. Potts, M.D.** — *Surgical Treatment of Patent Ductus Arteriosus*

173 **O. Theron Clagett, M.D.**, **James W. DuShane, M.D.** — *Diagnosis and Management of Coarctation of the Aorta in Children*

181 **William L. Riker, M.D.** — *Anomalies of the Aortic Arch and Their Treatment*

197 **Egbert H. Fell, M.D.**, **Richard A. Forney, M.D.** — *Surgical Treatment of Congenital Cardiovascular Anomalies Accompanied by Cyanosis*

215 **Richard Langendorf, M.D.**, **Alfred Pick, M.D.** — *Cardiac Arrhythmias in Infants and Children*

235 **Frank R. Johnson, M.D.** — *Cardiac Hypertrophy in Infancy*

251 **Donald E. Cassels, M.D.** — *The Diagnosis of Rheumatic Fever*

265 **Charles H. Rammelkamp, Jr., M.D.**, **Bertrand L. Stolzer, M.D.** — *The Treatment and Prevention of Rheumatic Fever*

275 — *Index*

FOREWORD

WILLIS J. POTTS, M.D.
STANLEY GIBSON, M.D.

Specialization continues to grow in the fields of medicine, constantly enriched by the addition of new facts, refinements and insights. For many years Pediatrics has been recognized as a specialty of Medicine and has in turn developed subspecialties of its own, of which one of the latest and most important is pediatric cardiology.

However, there may be a gain in understanding if we think of Pediatrics, not as a specialty of Medicine, but as a discipline of Medicine confined to a special group of people and embracing all the facets and facts of internal medicine and surgery. In short, Pediatrics *is* Medicine and differs from its usual practice only so far as the child cannot be regarded as a miniature adult in formulating the means to effective diagnosis and therapy.

This belief underlies publication of the PEDIATRIC CLINICS OF NORTH AMERICA and brings into proper perspective a decision to devote its first issue to a relatively new aspect of pediatric practice. Just as the conscientious internist schools himself in the complex problems of cardiology, so must the pediatrician and the practitioner who cares for the well or ill child understand the clinical uses of many special skills and techniques. From this point of view, our surveys of the complex problems presented in cardiac catheterization, in techniques of cardiac surgery, in angiocardiography and electrocardiography, in the intricate phases of rheumatology, represent not excursions into the esoteric, but simple exposition of what must be known by the physician confronted with problems of diagnosis and treatment of heart disease in children.

A heart murmur in a child is important only when its significance is understood. A short, harmless-sounding murmur may be associated with serious pathology which can be corrected surgically; a noisier murmur calling undue attention to itself, but entirely harmless, may be the reason for mistakenly placing a child at prolonged bed rest.

Pediatric Surgery is one the least developed branches of Medicine. Progress in this field, especially in the surgical treatment of congenital deformities, has been more rapid than the development of facilities for training surgeons. In the course of time—perhaps a generation—there will be trained pediatric surgeons in every children's hospital. To this end it is important that the pediatrician or practitioner know what is good surgery and what type of surgery should be done for his patients. Therefore the editors hope that in the future the Pediatric Clinics will continue to include articles on the surgical treatment of diseases peculiar to children. Ideally, the surgeon should follow medical advances and the pediatrician should familiarize himself with progress in surgery. So much to do, so little time! Perhaps if this new endeavor for the dissemination of pediatric knowledge included something of pediatric surgery, briefly written and well illustrated, the harassed clinician, after a long day's work and between telephone calls, might with fleeting glances pick up bits of surgical knowledge. The surgeon too will find helpful and enlightening insights in the entirely medical articles, for the surgeon must act, not as a directed agent, but as an understanding participant in the regimen for cure.

So important do we feel the detailing of such knowledge to be that we have undertaken the editorship of this symposium with pleasure, and we wish this new venture in medical literature the success which useful knowledge will deserve. The contributors to this issue have been chosen almost without exception from the Middle West. Friendships have been imposed upon in order that the best material might be assembled. To all the contributors the editors and publisher are deeply grateful.

Finally, but most important of all, this first issue is dedicated to the child "with something the matter with his heart."

EYES, HANDS AND EARS IN THE DIAGNOSIS OF HEART DISEASE IN CHILDREN

STANLEY GIBSON, M.D.

A wide variety of methods is used in the study of heart disease in children. The x-ray film, the fluoroscopic study, the electrocardiogram, angiocardiography, retrograde aortography, cardiac catheterization—all these and many more may be utilized in gaining information which serves to point up the diagnosis. These methods are chiefly valuable, however, to confirm or rule out a diagnosis suggested by previous clinical observation. Hence the various diagnostic aids should be used to supplement and not to replace the solid information which only a careful history and physical examination can supply. In the recent edition of his textbook on heart disease, Dr. Paul White estimates the history at 45 per cent and the physical examination at 25 per cent of the total examination of the cardiac patient. He places the electrocardiogram next in importance at 15 per cent, x-ray studies at 10 per cent, and all other studies at 5 per cent. One would doubtless modify these figures somewhat in the heart disease of children, chiefly in the direction of greater stress on the physical examination.

When one approaches a child with a view to evaluating his cardiac status, it is important to keep in mind the types of heart disease from which children suffer. With relatively few exceptions, chronic heart disease in a child is due either to congenital or to rheumatic heart disease.

HISTORY

The history in suspected cases of congenital heart disease should begin with the mother. For the most part there is no definite knowledge regard-

From the Children's Memorial Hospital, Chicago.

ing the etiology of congenital cardiac malformations. The parents of children who have congenital cardiac malformations bear no hereditary taint. Their health is as good as that of other persons. There is the one important exception that when the mother has an attack of German measles in the first trimester of pregnancy, and especially in the first two months, there is a great likelihood that the baby will be the victim of congenital heart disease, congenital cataracts, deafness or mental retardation. The most frequent congenital cardiovascular anomaly in this situation is a patent ductus arteriosus. Cyanotic congenital heart disease is rarely seen in the German measles baby.

The history of events during the neonatal period and throughout the first year of life is important. *Cyanosis* is one of the most significant signs in congenital heart disease, and upon its presence or absence is based one's clinical approach to the diagnosis of the specific lesion. Often cyanosis is present during the first days of life, disappears after a short while, and never recurs. When such a history is obtained, one may suspect that the cause of the cyanosis was atelectasis or some other condition not related to the circulatory system. In severe congenital heart disease, cyanosis may be present at birth, continue without interruption, and become more severe as the child grows older. Such is likely to be the case in transposition of the great vessels, tricuspid atresia, the Taussig heart and severe tetralogy of Fallot. Cyanosis may not be present until the child is several months or even several years old. In the milder cases of tetralogy of Fallot, and in pulmonary stenosis with intact ventricular septum and open foramen ovale, cyanosis may not be observed until late infancy. In the Eisenmenger complex, cyanosis usually appears in later childhood.

The rate of growth and development may be important in determining the severity of a congenital cardiac malformation. There is often a story of insufficient gain in weight, feeding difficulties and gastrointestinal upsets. Rapid *labored respiration* is often the only thing which leads the mother to believe that something is wrong with her baby. It should be regarded as an important sign, for in the noncyanotic infant it may be a manifestation of one of the rarer forms of heart disease in early life, such as an anomalous left coronary artery arising from the pulmonary artery, fibroclastosis or glycogen storage disease.

The presence of "*spells*" during infancy and early childhood must be carefully evaluated. In any young patient who has had a diagnosis of heart disease, every real or imaginary symptom is likely to be attributed to the cardiac ailment. Moreover in severe anoxia, attacks of paroxysmal dyspnea occur in which difficult breathing, extreme cyanosis, limpness, convulsions and even unconsciousness may supervene. Often, however, spells occur more or less similar to those just described in which there is no history of cyanosis, but, because of the presence of a congenital heart lesion, they are naturally assumed to be due to the cardiac lesion. In such instances

the entire child should be studied with great care, particularly with regard to his nervous system.

Not infrequently convulsive attacks due to epilepsy or other neurologic disturbance are mistaken for true attacks of paroxysmal dyspnea due to anoxia. I have more than once seen such attacks completely relieved by the judicious and long-continued use of phenobarbital. The differentiation is important, inasmuch as it may profoundly influence one's opinion of the seriousness of the cardiac condition.

In the child who has begun to walk it is important to know whether he is able to keep up with other children. This is often difficult to assess from the parents' story, for if they have been told that he has a heart murmur, they watch him closely and anxiously and tend to exaggerate the slightest symptoms. A really important symptom, one that should always be inquired about without asking a leading question, is that of squatting to rest when tired. It apparently occurs only when there is an insufficient supply of blood to the lungs. It is seen almost without exception in cases of the tetralogy of Fallot, much less often in pulmonary stenosis with intact ventricular septum and rarely in transposition of the great vessels. In instances in which the presence of pulmonary stenosis is in doubt, a history of squatting just about answers the question in the affirmative.

In searching for evidence pointing towards rheumatic fever a history of *sore throats* is significant. A streptococcal throat infection almost always precedes a rheumatic episode, yet sore throats occur so frequently in children that such evidence is of limited value. Much more important is a history of *joint pains*, and utmost patience and care must be exercised in obtaining the facts. I am firmly convinced that a thorough inquiry into the nature of so-called arthritic pains may be the most important link in the chain of evidence which establishes or rules out a rheumatic episode. The joint pains of rheumatic fever are fleeting, usually involving several joints in rapid succession. Pain in a single joint, pain which lasts only a few minutes, pain occurring only at night, pain limited to the lower extremities, pain relieved by rubbing—none of these is likely to be rheumatic and should not be so considered without the closest scrutiny. Certainly the nondescript growing pains limited to the muscles are not in themselves indicative of a rheumatic invasion. A previous chorea in the opinion of most rheumatologists places the child in the rheumatic group.

PHYSICAL EXAMINATION

Inspection

The physical examination should first of all consist of an appraisal of the patient's general appearance: the nutritional state, the presence of deformities, the tonus of the muscles and the color of the skin. Many congenital cardiac anomalies may interfere with normal growth and develop-

ment. Visible movements of the chest wall over the cardiac area give valuable information concerning the size of the heart and whether the heart is tumultuous in its action. Distinct pulsations in the suprasternal notch immediately suggest coarctation of the aorta or aortic insufficiency, the one being a congenital malformation, the other due almost always to rheumatic fever.

Most important of all is the color of the skin. The presence or absence of *cyanosis* is the point of departure in reaching an anatomic diagnosis in congenital heart disease. Constant cyanosis indicates that a considerable amount of blood is being shunted from the venous to the arterial circuit. One's thoughts are immediately directed to such cardiac malformations as the tetralogy of Fallot, tricuspid atresia, pulmonary stenosis with open foramen ovale, the Taussig heart or transposition of the great vessels. The distribution of the cyanosis should be observed. If one detects a distinctly greater cyanosis of the hands than of the feet, it practically makes the diagnosis of transposition of the great vessels with patent ductus arteriosus. It means that oxygenated blood from the pulmonary artery is entering the descending aorta, thus increasing the oxygen content of the blood flowing to the lower extremities. On the other hand, if the head and upper extremities show no cyanosis and there is blueness of the lower extremities, one can be practically certain that the patient has an infantile type of coarctation with a patent ductus arteriosus or an interruption of the aortic arch. In this case venous blood from the pulmonary artery enters the descending aorta. If cyanosis is doubtful or absent at rest, it may often be observed when the patient cries or exercises. Clubbing of the fingers and toes occurs when cyanosis has been present for a considerable period. Even in severely cyanotic infants one rarely observes clubbing before the fourth or fifth month of life.

It is an interesting fact that two of the five cardinal manifestations of rheumatic fever are revealed by careful inspection. The pinkish wavy lines, roughly circular in outline, and a centimeter or two in diameter, known as *erythema annulare*, are now generally conceded to be a rheumatic manifestation. The rash appears on the trunk and extremities. It does not itch or sting, is evanescent, and is easily overlooked unless it is carefully sought.

The presence of rheumatic nodules tells a whole story. It means that the patient is a rheumatic subject, that he has been ill for a considerable period, that he almost surely has fairly severe rheumatic carditis, and that convalescence will be slow.

Palpation

The hands are too little used in arriving at a cardiac diagnosis, nor should their use be limited to the area of the heart. For years I have made it a rule to palpate the femoral arteries before exploring the region of the

heart itself. Absent or weak pulsations of the femoral arteries with vigorous pulsations of the radial arteries justify a diagnosis of coarctation of the aorta.

Distinct pulsations of the liver in a patient with congenital heart disease immediately suggest a diagnosis of pulmonary stenosis with intact ventricular septum or tricuspid atresia. Gross enlargement of the liver raises the question of congestive heart failure, though an easily palpable or moderately large liver is so frequently found in infants and children that it should be evaluated with caution. One frequently encounters the liver edge an inch or more below the costal margin in the nipple line with no other signs suggestive of cardiac failure, in fact with no evidence of disease whatsoever.

A *thrill* felt in the first right interspace and in the suprasternal notch is practically diagnostic of congenital aortic or subaortic stenosis. A thrill over the heart itself gives valuable information. A systolic thrill maximal in the fourth left interspace points towards a defect of the ventricular septum, whereas a systolic thrill in the second left interspace is found in pulmonary stenosis and patent ductus arteriosus. Sometimes the thrill of a patent ductus may extend through systole and the greater part of diastole, and thus is practically diagnostic of a patent ductus. The thrill which occurs in rheumatic heart disease in children is due in almost all instances to mitral stenosis, is felt at the apex and is presystolic in time. Its timing is established by the fact that the thrill ends abruptly as one feels the thrust of the apex of the heart against the palpating hand.

Percussion

Percussion alone yields information that may establish a diagnosis. By this means one is able to determine roughly the size of the heart, but more important is the heart's position. Occasionally the cardiac dullness is found on the right. In such an instance it is important to know the position of the abdominal viscera. If liver dullness is found on the left side of the abdomen, and stomach tympany on the right—in other words, a complete situs inversus—heart disease may or may not be present. In most instances of mirror image position of all the viscera, no cardiac pathology is found. If, however the heart is on the right and the abdominal organs are in their normal position, serious congenital heart disease is often present. It is spoken of as isolated dextrocardia. From the results of autopsy studies in this condition one can state with fair confidence that severe pulmonary stenosis with a single ventricle or a large ventricular septal defect will be found. Likewise if an isolated levocardia is found—that is, the heart in normal position with the liver and stomach transposed—the diagnosis is usually that of tetralogy of Fallot with probable additional anomalies such as an auricular septal defect or anomalies of the venous return.

Auscultation

Auscultation is in my opinion by far the most important single procedure in arriving at a cardiac diagnosis in children.

Cardiac Murmurs. In doubtful cases the presence or absence of heart disease most often revolves about the significance of a cardiac murmur. Heart disease in a child in the absence of a murmur is infrequent. On the other hand, the presence of a murmur is by no means evidence of the presence of heart disease. If one listens carefully to the hearts of children between the ages of two years and the beginning of adolescence, a murmur will be heard in well over 50 per cent. This functional murmur has characteristics which usually enable the examiner to distinguish it from the murmurs of organic heart disease.

Functional murmurs are systolic in time. They are usually maximal above the apex, most often in the pulmonary area, sometimes in the third or fourth left interspace near the sternum. They are empty-sounding, not having the blowing quality characteristic of organic murmurs. They are poorly transmitted, usually better heard when the patient is in the recumbent position, and vary in intensity from one examination to another. Everyone has ample opportunity to familiarize himself with this type of murmur. He has only to listen to the hearts of a large group of healthy children.

In addition to functional murmurs there are other innocent sounds which may be misinterpreted. Most important of these is the *venous hum.* This is a blowing or roaring sound continuing through the cardiac cycle, usually best heard in the neck, louder on the right side than on the left. It is often heard over the anterior chest beneath the clavicles and, when loud on the left side, may be mistaken for a patent ductus arteriosus. Yet it should not cause confusion. The hum is best heard when the patient is in the sitting position, and becomes less marked or even disappears when he lies down. Pressure upon the neck veins, obstructing the flow of blood, causes it to disappear.

Organic murmurs are due in almost all instances to either rheumatic or congenital heart disease. The patient's history and age are important in differentiating between congenital and rheumatic involvement of the heart. A murmur heard in a child under the age of three years is likely to be congenital in origin. On the other hand, a heart murmur heard in an older child, in whom earlier examinations had failed to elicit a murmur, is evidence in favor of a rheumatic lesion. A history of joint pains is important supporting evidence.

In most instances, however, it is relatively easy to differentiate between rheumatic and congenital heart disease without asking a single question. A proper appreciation of the pathology in the two types of heart disease is essential in the interpretation of murmurs.

MITRAL VALVE. Numerous postmortem studies have established the fact

that in rheumatic heart disease the mitral valve is practically always involved. Three different murmurs may result from mitral damage. The first murmur to be heard, if one has the opportunity to examine the heart early in the course of the rheumatic invasion, is a soft blowing *systolic murmur* maximal at the apex with transmission towards the axilla. Whether this murmur, often heard within a few days after the appearance of rheumatic polyarthritis, is due to actual inflammation of the mitral cusps or to cardiac dilatation from an accompanying myocarditis, it is difficult to say. In any event it may be regarded as evidence of organic cardiac involvement. In mild cases the murmur may disappear after some weeks. But if the murmur persists, it is good evidence of mitral damage.

Shortly after the appearance of the systolic murmur, an early *diastolic rumble* may be heard. It is also heard at the apex, often localized, and occupies in the cardiac cycle the position of the third heart sound. This murmur, together with the systolic murmur, offers added evidence of mitral involvement.

Finally, in long-standing cases after the valve has become scarred and contracted, a third murmur may be heard at the apex. This is the familiar *presystolic murmur*, occurring in late diastole and ending abruptly with the first heart sound. The presystolic murmur may be sharply localized in the region of the apex, and may be missed unless this entire area is carefully explored. It is better heard in the recumbent position than when the patient is sitting, and best of all when the patient is in the left lateral position.

Thus one may hear three distinct murmurs at the apex in rheumatic valvulitis. In mild cases the systolic murmur alone may be heard. In other instances a mid-diastolic rumble is also audible. Finally a presystolic murmur may appear, and all three murmurs may be present at one time. In a certain percentage of cases the valve may heal to the extent that the murmurs are no longer heard. This is especially true of the systolic and mid-diastolic murmurs, but once a presystolic murmur has been well heard, it usually persists.

TRICUSPID VALVE. The tricuspid valve is not infrequently involved in the rheumatic process, but is usually less damaged than the mitral valve, and the findings are so similar to those occurring in disease of the mitral valve that the diagnosis is rarely made.

AORTIC VALVE. Involvement of the aortic valve is next in frequency and importance to that of the mitral valve. Roughening and thickening of the cusps cause insufficiency of the valve, manifested by a blowing *diastolic murmur* beginning with the second heart sound, and best heard along the left sternal margin at about the third left interspace. This murmur, particularly in its earlier stages, is short and soft and may be easily missed. It is much better heard with the Bowles type of stethoscope than with the bell; in my own experience, the best means of all is the naked ear applied

to the chest. It is usually easy to distinguish this murmur from the diastolic murmurs of mitral disease because of the difference in timing and location.

In older patients with long-standing rheumatic heart disease, aortic stenosis may occur, producing a coarse systolic murmur and thrill in the first and second right interspaces. This, however, is a late finding and is rarely encountered in children. Slight involvement of the pulmonary valve is occasionally found at autopsy, but it is clinically unimportant.

Thus four murmurs are important in the rheumatic heart disease of childhood, three heard at the apex due to involvement of the mitral valve and one heard along the left sternal border due to aortic insufficiency. If one wished to be dogmatic, he could state that these are the only murmurs important in arriving at a diagnosis of rheumatic carditis in children.

Friction Rub. A friction rub may be heard over the precordial area in the course of active rheumatic carditis or in pericarditis due to other causes. It is characteristically scratchy or scraping and is heard in both systole and diastole. It may be maximal over any portion of the cardiac area or even beyond the borders of the heart. A friction rub may obscure cardiac murmurs, so that their evaluation should not be undertaken until the rub has disappeared. The presence of a significant murmur after the rub has disappeared is strong evidence of a rheumatic process. The absence of a murmur suggests that the pericarditis is nonrheumatic in origin.

Congenital Heart Murmurs. As in rheumatic heart disease, knowledge of the pathology of congenital heart disease is essential in interpreting the various murmurs produced. In the majority of cases of congenital heart disease there is an abnormal communication between the arterial and venous circuits, occurring almost always by way of a patent ductus arteriosus, an auricular septal defect or a defect of the ventricular septum. In 1000 cases of congenital heart disease reported by Abbott, there were existing alone or in combination with other lesions 257 examples of defect of the ventricular septum, 290 of auricular septal defect or open foramen ovale, and 242 of patent ductus arteriosus. Passage of blood through these abnormal openings usually produces a murmur.

VENTRICULAR SEPTUM. In a localized defect of the ventricular septum one hears a harsh blowing systolic murmur maximal at about the fourth left interspace near the left sternal margin. The murmur is almost always heard at the first examination in the newborn period and persists with little change through infancy and childhood. It is usually widely transmitted. This murmur varies in intensity, but is usually loud and accompanied by a thrill.

PATENT DUCTUS ARTERIOSUS. The full blown murmur of a patent ductus arteriosus is the most dramatic murmur in the entire field of cardiology. The murmur is rumbling, practically continuous through systole and dias-

tole, and best heard in the second left interspace, though almost equally well heard in the first left interspace. In the third left interspace the diastolic phase is markedly diminished or drops out altogether. In more than 250 cases of uncomplicated patent ductus arteriosus coming to operation at Children's Memorial Hospital, we have found this description accurate in practically every instance. In fact, if the murmur fails to fill these specifications, we hesitate to make the diagnosis. It must be understood, however, that the characteristic murmur of the patent ductus arteriosus is of slow evolution. I have never heard the typical continuous machinery murmur in a newborn infant. In exceptional instances it may be heard in the early months of life. More often the systolic phase alone is heard in infancy, the diastolic element appearing from the first to the third year of life. When a patent ductus arteriosus occurs in combination with other lesions—for example, in conjunction with coarctation of the aorta or transposition of the great vessels—the murmur is rarely typical, and the presence of a patent ductus may not even be suspected.

AURICULAR SEPTUM. As our knowledge of defects of the auricular septum has increased, it has been possible to determine with some accuracy the type of murmur which occurs in this condition. The murmur is usually less loud and harsh than that heard in defect of the ventricular septum. It is usually systolic in time and best heard in the second or third left interspace. It is rarely accompanied by a thrill. Wide splitting, with little or no increase in intensity of the second pulmonic sound, is frequent and is an important diagnostic point.

PULMONIC STENOSIS. In addition to the lesions permitting a flow of blood between the systemic and venous circuits, there are congenital defects involving the valves. Most important of these is pulmonic stenosis. This lesion causes a systolic murmur best heard in the second or third left interspace. It varies greatly in intensity. It is heard in pure pulmonary stenosis, tetralogy of Fallot, pulmonary stenosis with open foramen ovale and in tricuspid atresia.

AORTIC STENOSIS. Congenital aortic or subaortic stenosis is a fairly frequent lesion. It produces a coarse systolic murmur best heard to the right of the sternum in the first or second interspace.

Diastolic murmurs are relatively infrequent in congenital heart disease. One may, however, hear a diastolic murmur along the left sternal margin in instances of the Eisenmenger syndrome due to an accompanying malformation of the aortic valve. A diastolic murmur in the second left interspace is often heard when the pulmonary artery is widely dilated as in auricular septal defect or the Eisenmenger syndrome. A mid-diastolic murmur at the apex occurs frequently when considerable enlargement of the heart has occurred from whatever cause.

By and large, however, the murmurs of congenital heart disease are

chiefly systolic in time, and maximal above the region of the apex. In rheumatic heart disease, three of the four characteristic murmurs are heard at the apex, and two of these occur in diastole.

Cardiac Hypertrophy. Finally there are types of heart disease occurring in infancy and childhood which are due neither to rheumatic infection nor to a congenital cardiac malformation in the usual sense. I refer to cardiac enlargement in infancy, usually associated with rapid breathing and often real dyspnea. Included in this group are fibroelastosis, left coronary artery arising from the pulmonary artery, interstitial myocarditis and glycogen storage disease. One of these conditions may be suspected when one encounters an infant who is having respiratory distress, usually with no cyanosis, and in whom one discovers cardiac enlargement by percussion and in whom no murmur or a faint systolic murmur is heard. The exact diagnosis depends upon other methods of examination.

VALUE OF CLINICAL STUDIES

In emphasizing the importance of the history and the physical examination in the diagnosis of heart disease in children, I do not wish to decry the use of laboratory studies. The x-ray film, the fluoroscopic study, the electrocardiogram, the angiocardiogram, cardiac catheterization—all these and other means of diagnosis may be necessary in the obscure case. In the average case only the simpler procedures such as x-ray studies and an electrocardiagram are necessary. In the puzzling case a thorough clinical knowledge to point the direction which the special studies should take is always important. One must remember, too, that the "gadgets" may lead one astray instead of supplying the desired information.

The seasoned clinician cherishes the pathognomonic sign. To observe a cluster of rheumatic nodules on the elbow and to be able to say from this sign alone that the child has had rheumatic fever over a considerable period of time, has chronic rheumatic heart disease and will be slow in making a recovery; to discover in a cyanotic infant a distinctly greater cyanosis in the hands than in the feet and from this simple observation to postulate a transposition of the great vessels with patent ductus arteriosus; to rule out a truncus arteriosus communis by hearing a split second sound over the pulmonary area: such observations remind one that the clinician may still make a worth-while contribution. Incidentally, he may spare the patient some disagreeable or even dangerous procedures, not to mention the financial saving to his family.

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FUNCTIONAL PATHOLOGY OF CONGENITAL CARDIAC DISEASE

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This communication deals with congenital cardiac diseases that may come to the attention of the pediatrician. Though it is primarily concerned with the pathologic aspects of these conditions, I have elected to group the conditions according to the frequent presenting complaints when medical attention is sought. In this way the congenital malformations of the heart and great vessels may be divided into three major groups as follows:

1. Complaints of poor development; improper rate of gain in weight, irritability and recurrent attacks of "pneumonia" or "bronchitis"; no cyanosis except possibly during attacks of pulmonary symptoms
2. Dyspnea on exertion; no attacks of pneumonia; no cyanosis.
3. Persistent cyanosis; complaints may or may not include attacks simulating pneumonia.

The first two groups of conditions may be referred to as *acyanotic* and the third group as *cyanotic* types of congenital cardiac disease. The three groupings represent only a working scheme, and at first examination it may not be easy even with the history to place every case with precision into one group or another. One of the difficulties over and above an inadequate history is the problem of determining whether a patient is cyanotic. In this discussion by the term "cyanotic" congenital cardiac disease is meant that there is incomplete saturation with oxygen of the systemic arterial blood. The present day use of the oximeter with and without use of dye dilution methods represents an aid of considerable magnitude in segregating patients of the first two groups from the third group.

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ACYANOTIC HEART DISEASE

Complaints of Poor Development

Conditions which may be responsible for improper body development and attacks simulating pneumonia are those in which left ventricular failure is present, those conditions primarily responsible for impaired pulmonary venous flow or malformations causing excess pulmonary blood flow without associated impediment to pulmonary venous flow.

Left Ventricular Failure. Several conditions may lead to left ventricular failure and to pulmonary congestion and pulmonary edema. Pneumonia and pulmonary hemorrhages may result from these complications. These conditions are ventricular septal defect, coarctation of the aorta, patent ductus arteriosus, aortic stenosis, subaortic stenosis and anomalous origin of the left coronary artery from the pulmonary trunk. If one reviews the clinical histories of patients dying during childhood and infancy with one or another of these conditions, a striking similarity is evident in the clinical pattern. Often symptoms are nonspecific, taking the form of poor appetite and failure to gain weight, irritability, listlessness and pallor. Attacks of "bronchitis" or pneumonia, either inferred or real, may be the most proximal manifestations of an intrathoracic disorder. Cyanosis, which characteristically is not present between attacks of "bronchitis" or "pneumonia," may be present during such attacks. In the pathologic evaluation of such cases the pulmonary difficulties often may be considered attacks of pulmonary congestion, edema and pneumonia, if present, representing a complication of the pulmonary edema. Though a cardiac murmur may suggest a cardiovascular disorder, one is not invariably present, and frequently the roentgenogram of the thorax taken to determine the nature and extent of the pulmonary condition shows cardiac enlargement. This observation may give the initial suspicion of the presence of a cardiovascular malformation.

VENTRICULAR SEPTAL DEFECT. Defects of the ventricular septum most commonly involve the membranous portion of the septum, where they are characteristically single (Fig. 1). Less common, but by no means rare, are defects of the muscular portion of the septum. Though muscular defects may be multiple, they are usually single.

The direction of the shunt in the presence of a ventricular septal defect depends upon the differences in resistance to flow through the pulmonary circuit on one hand and through the systemic circuit on the other.[1, 2] If the resistance to pulmonary flow is high, the flow may be from right to left, resulting in incomplete saturation of the hemoglobin in the blood of the systemic arterial system. Such cases are to be classed with the cyanotic types of congenital heart disease.

Here we are concerned with the type of ventricular septal defect in which this is an essentially normal difference in resistance to flow and in

pressure between the two circulations. Under these circumstances the flow through the defect is from left to right. The systemic arterial blood is saturated with oxygen. The pulmonary circuit receives the saturated blood of the shunt as well as the venous blood returning to the right side of the heart, and the volume of pulmonary blood flow is excessive. The shunted blood is carried by both ventricles. The frequent complications of pulmonary congestion, edema and hemorrhage may be attributed to left ventricular failure coupled with excess pulmonary flow.

Although some regard ventricular septal defect as a benign condition, death in early infancy from the pulmonary complications is common.[3]

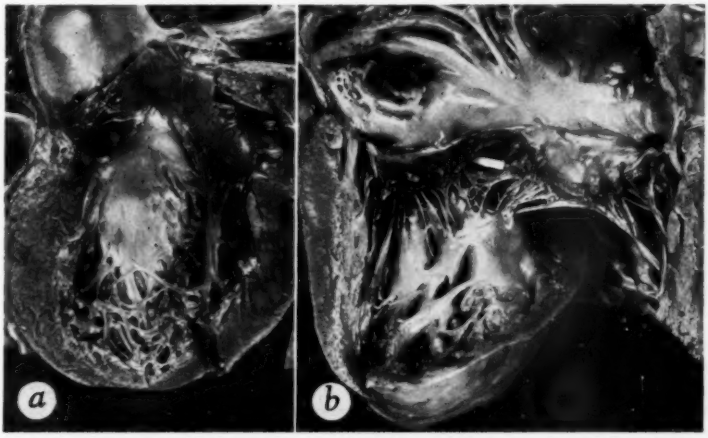

Fig. 1. *a*, Left ventricle from a 3 month old boy. Inferior to the aortic valve is a membranous ventricular septal defect. *b*, Right side of heart. Probe presenting in right atrium also lies in membranous ventricular septal defect. Characteristically there is close proximity between the tricuspid valve and membranous ventricular septal defects. At times, as suggested in this case, some of the shunted blood enters the right atrium in addition to the right ventricle.

In the pathologic collection of the Mayo Clinic there are thirty specimens of ventricular septal defect without associated malformations and in patients who were born alive. Among the patients from whom the specimens were obtained, 19 had died before they reached the age of six months.

It appears that in those patients who survive the critical six postnatal months, adaptation to excess pulmonary flow is reasonably well tolerated. Among this group the major serious complications are congestive cardiac failure and bacterial endocarditis.[4, 5] An occasional patient with membranous ventricular septal defect may acquire fibrotic changes in the neighboring aortic valve, the valvular changes resulting in aortic insufficiency and the clinical picture resembling patent ductus arteriosus.[6, 7]

In an unusual instance a ventricular septal defect is associated with pulmonary stenosis, but with the shunt in the left-to-right direction.[8, 9]

COARCTATION OF THE AORTA. There are two common misconceptions regarding coarctation of the aorta: (1) that coarctation in the absence of other malformations does not interfere with the welfare of the infant or child, and conversely (2) that when coarctation is productive of symptoms in early life, it is associated with other serious cardiovascular malformation.

The reported experience of several groups in the past few years indicates beyond any doubt that at times coarctation without associated

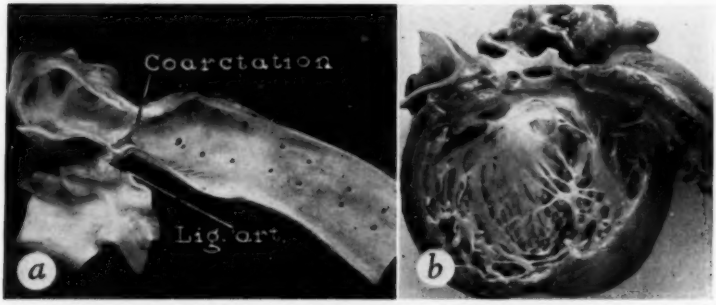

Fig. 2. Coarctation of the aorta proximal to closed ductus arteriosus in a female infant who died of acute pulmonary edema at the age of 5 months. *a*, The pulmonary arteries, ligamentum arteriosum and thoracic aorta. The coarctation lies proximal to the ligamentum arteriosum (*Lig. art.*). The intercostal arteries are not appreciably dilated. *b*, Left ventricle: hypertrophy and dilatation; bicuspid aortic valve.

malformations may be responsible for disability[10, 11] and death in infancy.[12–16] In the usual instance in which this is observed, the coarctation lies proximal to the ductus arteriosus, which is either closed or closing (Fig. 2). The functional disturbances leading to left ventricular hypertrophy and failure result from the obstructive hypertension of the coarctation in association with inadequate collaterals.

Although the foregoing type of situation occurs at times and may be responsible for the death of an otherwise normal infant, in the usual case of coarctation the aortic lesion lies beyond a closed ductus arteriosus. In such a case collaterals are well developed, and though the expected life span of the patients is far below average, symptoms usually do not occur until adolescence or adult life. Even in patients with well developed collaterals, "notching" of the ribs is not usually seen until after childhood.[17] In unusual cases associated malformations or the disposition of the coarctation may be responsible for unequal pulses.[18] In a boy aged eight years McGregor and Medalie[19] described absence of perceptible pulses in the four extremities.

COARCTATION AND COEXISTENT PATENT DUCTUS ARTERIOSUS. When the coarctation lies *distal* to a patent ductus arteriosus, left ventricular failure from the load of the shunt and the systemic hypertension may occur. Such patients likewise are noncyanotic until pulmonary complications result. Serious pulmonary vascular changes with pulmonary hypertension and right ventricular hypertrophy may complicate the picture.[20]

When the coarctation lies *proximal* to a patent ductus arteriosus, there is a right-to-left shunt into the descending aorta. Such a condition is relatively uncommon and should be classed with the cyanotic types of congenital cardiac disease.

PATENT DUCTUS ARTERIOSUS. Patent ductus arteriosus is regarded by some as an innocuous condition in infancy and childhood. Though this is usually the rule, there are exceptional cases in which disability and death are caused in infancy or childhood by left ventricular failure resulting from patent ductus arteriosus.[20–24] To the pathologist such cases are striking, since at necropsy the otherwise negative findings emphasize that recognition of the condition during life might, with proper surgical therapy, have prevented death.

During the period 1947 through 1951 Dr. J. W. DuShane and I have had combined clinical and pathologic experiences with 4 cases of fatal patent ductus arteriosus in which the patients were infants or children. The ages and sexes were as follows: males, 6 weeks and 3 months; females, 8½ months and 3 years. In each case the patent ductus was the only malformation of note. In each at necropsy there was left ventricular hypertrophy and pulmonary congestion, edema and focal hemorrhages (Fig. 3). The pulmonary complications were considered the immediate cause of death in each case.

In an occasional case a ductus arteriosus may be present on the right side.[25]

The experience with these cases has served to emphasize the fact that the manifestations of patent ductus arteriosus in infants and young children may be different from those of older children and adults. This has led to the clinical suspicion of this condition in certain infants with symptoms and to successful surgical closure of the ductus with restoration of health.

The evidence obtained from cardiac catheterization in young patients with patent ductus arteriosus is that at this early period pulmonary hypertension is common. When symptoms result from patent ductus arteriosus in infancy and early childhood they are usually caused by left rather than right ventricular failure.

AORTICOPULMONARY FISTULA. Aorticopulmonary fistula, sometimes called *aortic septal defect*, is represented by a window-like opening between the pulmonary trunk and the ascending aorta (Fig. 4). This relatively uncommon condition may give considerable difficulty in the clinical distinction from patent ductus arteriosus.[26] The functional disturbances in this condition are identical with those in patent ductus arteriosus.[27–29]

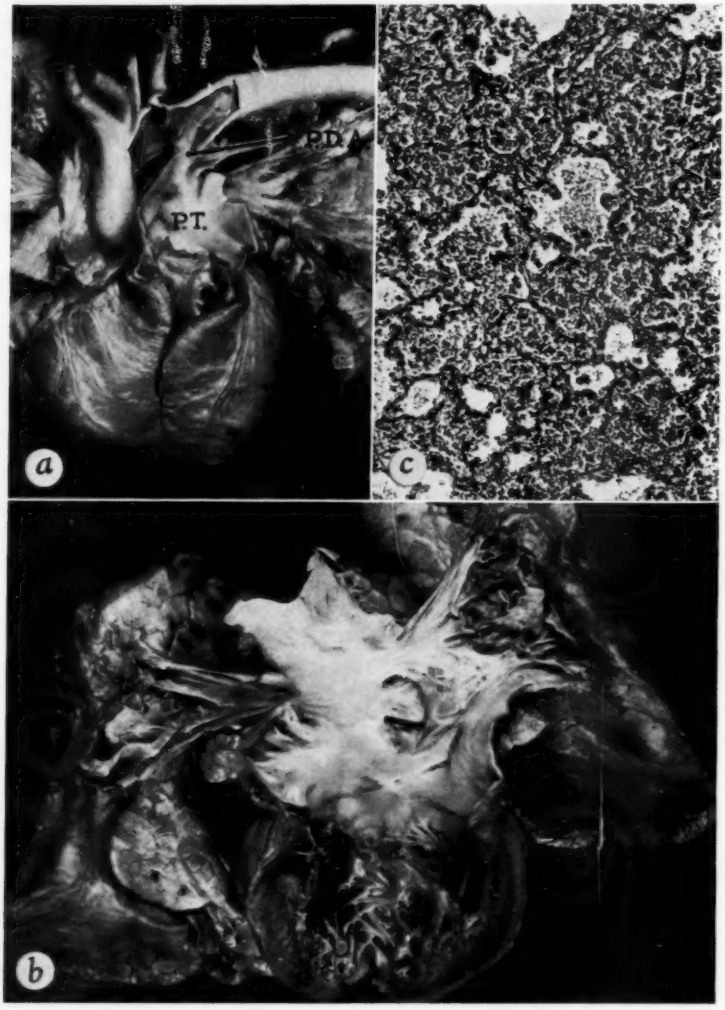

Fig. 3. Patent ductus arteriosus in a male infant dying at the age of 3 months. *a*, Heart and great vessels. A patent ductus arteriosus connects the aorta and the pulmonary arterial system. *P.D.A.*, patent ductus arteriosus: *P.T.*, pulmonary trunk. *b*, Left side of heart; dilatation of left atrium; left ventricular hypertrophy; probe present in an incidental "probe-patent" foramen ovale. *c*, Photomicrograph of lung showing extensive hemorrhage. (Hematoxylin and eosin; × 100).

Because of the character and position of the abnormal opening, aorticopulmonary fistula represents a surgical problem still unsolved.

ANEURYSM OF AN AORTIC SINUS. Aneurysm of an aortic sinus (sinus of Valsalva), an uncommon condition, usually involves the right and, less commonly, the posterior aortic sinus. The communication lies between the aorta and the right atrium or the right ventricle. Such communications may be on a congenital basis,[30] but more commonly they occur after rupture of the sinus aneurysm.[31–33] The functional disturbance of a sinus aneurysm which communicates with the right side of the heart is characterized by a left-to-right shunt in which blood of the aorta is carried into the right side of the heart, recirculated through the lungs and the left side of the heart, only to be returned to the right side. Such a functional disturbance gives rise to added work on the part of both ventricles, and failure may be represented either by typical right-sided congestive cardiac failure or by left ventricular failure with pulmonary congestion and edema.

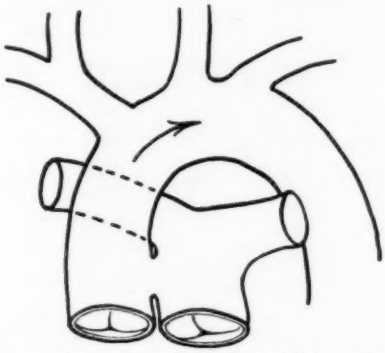

Fig. 4. Aorticopulmonary fistula. Above the valve level the ascending aorta and the pulmonary trunk communicate by a fistulous opening.

The patient with an acquired rupture of an aortic sinus usually has a history of normality until sudden onset of serious respiratory symptoms associated with the appearance of a continuous precordial murmur.

In addition to the complication of cardiac failure, an aortic sinus aneurysm may be associated with bacterial endocarditis originating either on the edges of the aneurysm or on those areas in the right side of the heart which are traumatized by the jetlike stream of blood flowing through the abnormal opening.

AORTIC STENOSIS: SUBAORTIC STENOSIS. Among conditions causing left ventricular failure in infancy and childhood, it is uncommon to encounter the primary lesion in the region of the aortic valve. Such lesions, when they do occur, may take the form of stenosis of the aortic valve,[34] or, in

the presence of a normal aortic valve, there may be obstruction in the outflow tract of the left ventricle, a condition called *subaortic stenosis*.[35]

In 2 cases of aortic stenosis which we have examined pathologically, one involved a male infant 5 days of age and the other a boy 2½ years old. In the first case the two leaflets of a bicuspid aortic valve were fused in such a way as to cause narrowing of the valve orifice. In the second case the elements of three aortic leaflets could be identified as fused to form a structure with the characteristics of a truncated cone (Fig. 5). Especially in the latter case the aortic valve had an appearance similar to that of the pulmonary valve in isolated pulmonary valvular stenosis. From the specimens it appeared that the obstructions were such as to be amenable to correction by valvotomy.

The reader will not compare aortic stenosis with aortic atresia. In aortic stenosis there is an opening at the aortic valve, however small, and a shunt

Fig. 5. Congenital aortic stenosis. Aortic valve viewed from above. A probe has been placed in the stenotic opening at the center of the valve. From a male infant who died at the age of 2½ years.

does not necessarily characterize the functional state of hearts with this condition. In aortic atresia the aortic valve has no opening whatsoever, and a shunt from left to right must exist to allow blood to flow out of the left side of the heart. Usually the shunt is across the atrial septum, allowing the oxygenated blood returning from the lungs to mix with the systemic venous blood returning to the right atrium. The mixed blood is propelled by the right ventricle to the lungs and through a patent ductus arteriosus to the systemic circulation. Therefore in aortic atresia there is desaturation of the systemic arterial blood. Aortic atresia thus is properly classed with cyanotic forms of congenital cardiac disease, while aortic stenosis belongs to the group of acyanotic forms.

In subaortic stenosis the obstruction in the left ventricular outflow tract lies immediately beneath the level of the aortic valve. Though the basis for this obstruction is not entirely understood, it probably is primarily represented by a deformity in the muscular portion of the ventricular septum. Secondarily, fibrous tissue may be deposited in the endocardium over the zone of congenital narrowing, leading to accentuation of the obstruction. The secondary effects of subaortic stenosis are identical with those of aortic stenosis. There is left ventricular hypertrophy, and

failure of the left ventricle results in pulmonary edema. As a rule, though congenital aortic stenosis causes symptoms at an early age, subaortic stenosis frequently causes no symptoms until adult life, when cardiac failure and bacterial endocarditis represent its two major complications.

ANOMALOUS ORIGIN OF THE LEFT CORONARY ARTERY FROM THE PULMONARY TRUNK. Except under most unusual circumstances, coronary arterial origin from the pulmonary trunk does not involve both arteries.[36] Usually when a major anomaly of coronary arterial origin occurs, either the right or the left artery arises from the pulmonary trunk, while the other arises normally from the aorta.

On the basis of published accounts and our own experience, anomalous origin of the right coronary artery from the pulmonary trunk does not give rise to recognized abnormalities clinically, and the patients usually reach adult life.[37] Such was true among about one third of the cases reported in which the left coronary artery arose from the pulmonary trunk.[38] Among the patients with this form of the malformation who do have symptoms, however, life is short. The majority of these patients die when they are from three to twelve months of age.[39–42]

The pathologic characteristics of the heart in infants dying with anomalous origin of the left coronary artery from the pulmonary trunk include, in addition to the malformation, dilatation and hypertrophy of the left ventricle and scarring in the distribution of the left coronary artery. There may be endocardial fibrous thickening in the areas corresponding to the region of greatest left ventricular dilatation and scarring. Mural thrombi in these regions also may occur.

The basis for the scarring of the myocardium is probably myocardial infarction resulting from ischemia in the areas supplied by the anomalously arising vessel. It has been taught that this ischemia results from venous-type blood supplied to this region of the heart from the pulmonary trunk by way of the anomalous artery. Dr. Howard B. Burchell and I have considered a different view. Our reasoning is as follows: Patients with cyanotic congenital heart disease in whom the heart may be perfused with blood 60 to 80 per cent saturated under normal pressure from the aorta do not show infarcts. There is relatively free anastomosis between branches of the major coronary arteries. With the left coronary artery arising from the pulmonary trunk, the pressure exerted by the blood within it is low, and the lack of pressure may be the main factor bringing about the ischemia. Also, the direction of flow of blood in this artery may *not be from the pulmonary trunk* to the muscle, but the anomalous artery may carry blood saturated with oxygen from branches of the right coronary artery *to the pulmonary trunk*. Stated otherwise, the anomalous artery by its connection with branches of the right coronary artery acts as an arteriovenous fistula shunting away from the myocardial capillaries highly oxygenated blood. The ischemia of the myocardium therefore re-

sults from an inadequate supply of blood to the myocardium rather than from an adequate volume of blood, but of systemic venous character.

Since patients with congenitally single coronary arteries arising from the aorta do not suffer from inadequate blood supply to the myocardium,[43] it would seem proper to consider, if our reasoning is correct, whether therapy of anomalous origin of the left coronary artery from the pulmonary trunk should consist in interruption in continuity of the anomalous artery. This would convert the heart into one with a single artery arising from the aorta and in which the phenomenon of "run off" of arterial blood would be overcome. Against such a viewpoint, however, is the lack of any mention of dilatation of the anomalous artery in reports of this condition.

The cause of death during infancy in anomalous origin of the left coronary artery from the pulmonary trunk is left ventricular failure—either protracted from the inadequacy of the remaining mass of muscle or sudden as in certain cases of acquired coronary arterial disease.

Impaired Pulmonary Venous Flow. In conditions associated with left ventricular failure the important symptoms come from the pulmonary complications resulting from the altered dynamics incident to the failing left ventricle. In essence, the effects of left ventricular failure upon the pulmonary circulation are those of impaired drainage from the pulmonary veins. In the conditions already discussed the pulmonary symptoms depend upon the appearance of impaired pulmonary venous flow. This phenomenon is not part of the functional characteristics of the underlying conditions, but represents a complication characteristic of the failing left ventricle.

There are, on the other hand, a number of congenital conditions that have as a functional characteristic of the uncomplicated condition the feature of impaired pulmonary venous flow. These conditions are endocardial sclerosis, mitral insufficiency, mitral stenosis and stenosis of the common pulmonary vein (cor triatriatum).

ENDOCARDIAL SCLEROSIS. Endocardial sclerosis, variously called *endocardial fibroelastosis* and *endomyocardial fibrosis*, is characterized by pronounced endocardial thickening with connective tissue, predominantly elastic tissue. The left ventricle is the usual site of involvement.

Whenever a cardiac chamber dilates, its endocardium may become thickened. Such a phenomenon may be called *secondary endocardial sclerosis*. In this condition the degree of thickening is relatively minor. We are not concerned here with secondary endocardial sclerosis, but rather with *primary endocardial sclerosis*.

This condition, which is usually restricted to the left ventricle, is to be considered a malformation, although a conclusive explanation for its formation is still wanting.[44, 45] It leads to cardiac failure, usually in infancy and less often in childhood.[35, 46–49] Two types of primary endo-

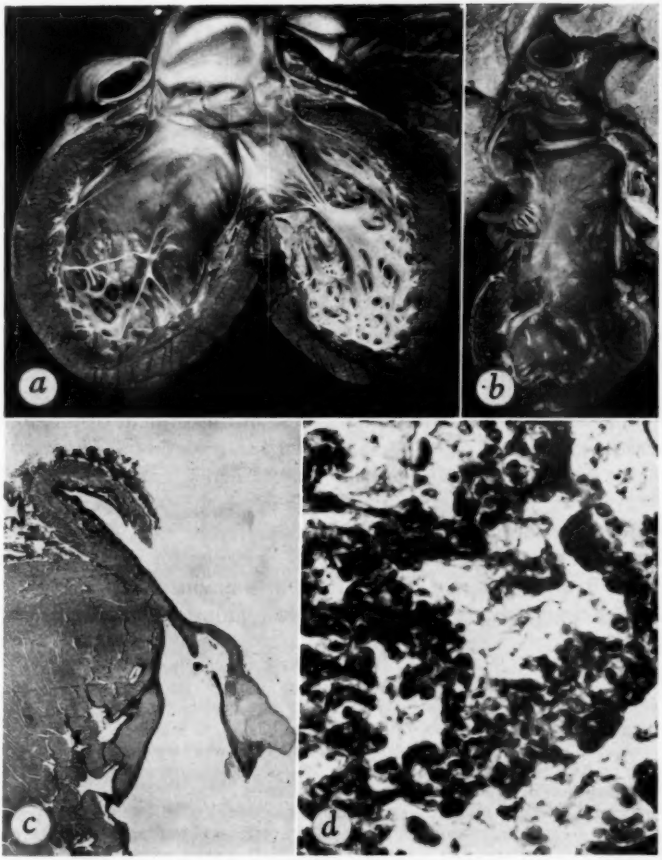

Fig. 6. Endocardial sclerosis, dilated and contracted types. *a*, Left ventricle in the dilated type of endocardial sclerosis, from a boy who died at the age of 9 months. *b*, *c* and *d*, Case of contracted type of endocardial sclerosis with mitral stenosis in an infant who lived only a few hours after birth. Specimen submitted by Dr. M. M. Patton. *b*, Left side of heart: dilatation of left atrium; fibrous thickening of endocardium of left ventricle; stenosis of mitral valve. *c*, Photomicrograph of longitudinal section through mitral valve and adjacent chambers. The endocardium of the left atrium and left ventricle are thickened by elastic tissue. Collagenous thickening of mitral valve leaflet. (Verhoeff's elastic tissue stain and counterstained with van Gieson's connective tissue stain; × 5). *d*, Photomicrograph of lung showing extensive congestion and edema. (Hematoxylin and eosin; × 300).

cardial sclerosis have been recognized—the dilated type and the contracted type.[50] Some cases previously considered exemplifying idiopathic hypertrophy probably represent primary endocardial sclerosis.

In the *dilated type* the left ventricle is greatly enlarged.[51] Its chamber is dilated and its wall is hypertrophied (Fig. 6, *a*). In the *contracted type* the left ventricular chamber is of normal size or smaller than normal. In the usual instance of primary endocardial sclerosis the cardiac valves are normal, although occasionally the aortic valve alone, the mitral valve alone or both valves additionally may be involved and be stenotic (Fig. 6, *b*, *c* and *d*).

Even in the absence of valvular involvement the mural endocardial thickening seems to exert its effect by splinting the left ventricle, preventing a normal excursion during the cardiac cycle. In the dilated type, examination of the specimen would suggest that the left ventricle is incapable of expelling most of its blood during systole, leaving a diastolic residual. This would represent a barrier to proper emptying of the left atrium, a barrier which would be reflected as impairment of pulmonary venous flow.

In the contracted type of primary endocardial sclerosis the thickened endocardium holds the left ventricle in a relatively contracted state, preventing proper degrees of diastolic dilatation. This too leads to an impediment of pulmonary venous flow.

Death is usually caused by an attack of pulmonary edema, although typical chronic right ventricular congestive failure may be manifest in some cases.

We have observed 2 interesting cases in which primary endocardial sclerosis of the left ventricle was associated with coarctation of the aorta and a degree of mitral insufficiency. One patient was a boy 4 years of age, the other a boy 15 years of age. In each case resection of the area of aortic coarctation and end-to-end anastomosis of the aorta were done. In each patient after removal of the clamps from the aorta there was a prompt fall in blood pressure and cardiac arrest.

In reviewing these 2 cases it appears that the endocardial sclerosis was responsible for a low and fixed cardiac output. With fall in peripheral resistance after the aortic obstruction was removed, the low and fixed cardiac output was incapable of maintaining an adequate level of systemic arterial blood pressure.

MITRAL INSUFFICIENCY. As a pure lesion, congenital mitral insufficiency is rare. This functional disturbance may result either from faulty formation of the valve, in which there is a cleft in the anterior leaflet, or from faulty disposition of the mitral chordae tendineae.[52]

Cleft formation of the anterior leaflet of the mitral valve is usually associated with an atrial septal defect, but we have observed two specimens each with a large cleft in the anterior leaflet of the mitral valve and with an intact atrial septum.

One case, the specimen of which was submitted by Drs. C. Hollis and L. S. Jolliffe, involved a boy who died of congestive cardiac failure at the age of 8 years.[18]

The specimen of the other case was submitted by Dr. John James. The patient, a 9 year old boy, had acute rheumatic pancarditis at the time of his death from congestive cardiac failure.

Abnormal disposition of the chordae tendineae as an isolated lesion is not a common condition leading to symptoms. We have seen this in association with endocardial sclerosis and in a case that also had a ventricular septal defect and patent ductus arteriosus.

We have also encountered "mitral" insufficiency in cases of corrected transposition of the great vessels. In this condition the aorta and pulmonary trunk are abnormally related to each other as in complete transposition of the great vessels. In contrast to the situation in the latter condition, however, in corrected transposition the abnormally disposed arteries connect with the ventricles in such a way that the blood takes a normal route. The right-sided ventricle appears as a mirror image of the normal left, and vice versa. Likewise the atrioventricular valves appear as mirror images of the normal. The left atrioventricular valve may be incompetent and give rise to mitral insufficiency.

In 4 specimens with corrected transposition which we have observed, 1 from a 60 year old man seemed to have functioned entirely normally. In 2, one from a 3 year old girl and another from a 31 year old woman, there was evidence of incompetence of the left atrioventicular valve. In the fourth case, involving a 10 week old female infant, there was the unusual situation in which the left atrioventricular valve had the deformity like that ordinarily involving the tricuspid valve and designated as Ebstein's malformation. This valve likewise seemed to have been incompetent.

MITRAL STENOSIS. Congenital mitral stenosis as an isolated lesion is rare.[53] More common, though unusual, is the occurrence of mitral stenosis in association with endocardial sclerosis of the left ventricle. Under any circumstance, congenital mitral stenosis usually causes death during infancy. An occasional patient will live to childhood, and then it frequently is difficult or impossible to tell whether the mitral stenosis is rheumatic or congenital in origin.

As with the aortic valvular lesions, it is important to distinguish between stenosis and atresia. In mitral stenosis a shunt is not essential for the flow of blood out of the left atrium, the stenotic mitral valve acting as a channel of exit for blood from this chamber. In mitral atresia it is not possible for blood to have a normal direction of flow out of the left atrium. In this condition an abnormal opening, usually in the atrial septum, allows blood of the left atrium to flow to the right. The mixture of blood in the right atrium ultimately supplies both the systemic and the pulmonary circulations. Since in mitral atresia there is desaturation of the systemic arterial blood, this condition is to be classed with the cyanotic forms of congenital cardiac disease.

ACCESSORY MITRAL VALVULAR TISSUE. An unusual form of obstruction of the mitral valve in a female infant who died at the age of 18 days was encountered by us (Fig. 7, *a*). A pedunculated mass of young connective tissue appearing as accessory valvular

tissue was attached to the atrial aspect of the mitral valve and obstructed the orifice of the valve (Fig. 7, *b*). Though in such a condition a shunt is not essential if some flow is allowed through the mitral orifice, it appeared that in this particular instance

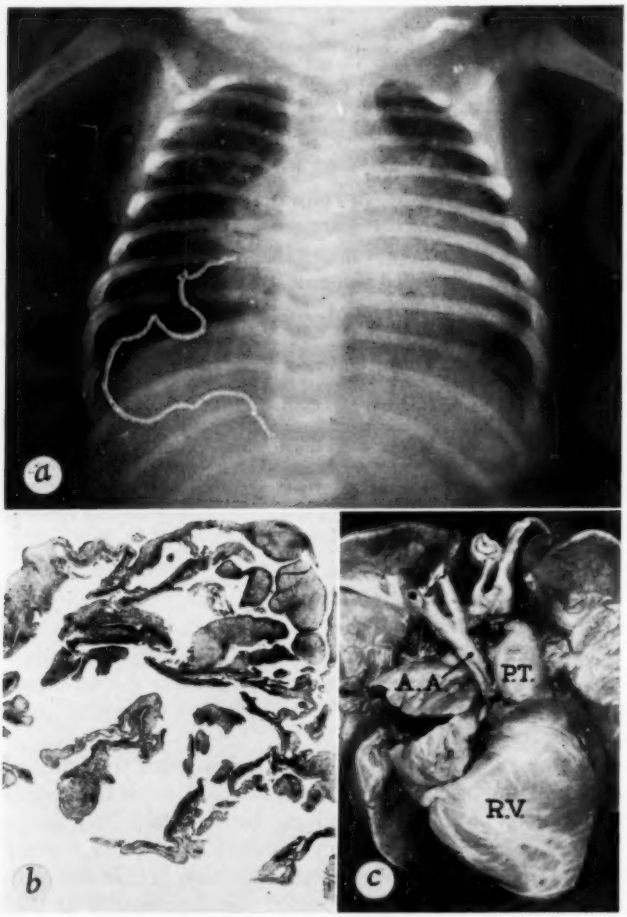

Fig. 7. Accessory tissue of mitral valve causing mitral obstruction. From a female infant who died at the age of 18 days. *a*, Roentgenogram of thorax. *b*, Photomicrograph of accessory tissue which obstructed the mitral valve. (Hematoxylin and eosin; × 10). *c*, Anterior view of heart and lungs. The right ventricle (*R.V.*) is hypertrophied. The pulmonary trunk (*P.T.*) is dilated, and the ascending aorta (*A.A.*) is hypoplastic. A patent ductus arteriosus and patent foramen ovale were present.

a left-to-right flow took place through a patent foramen ovale and that the mixture of systemic venous and pulmonary venous blood was distributed by the right ventricle partly to the pulmonary arteries and through a patent ductus partly to the aorta.

The right ventricle was enlarged and hypertrophied, the left ventricle small, the aorta hypoplastic and the pulmonary trunk wide (Fig. 7, *c*.)

Hypothetically, recognition of such a lesion and removal of the mass of accessory tissue might allow normal function.

COR TRIATRIATUM. Another condition which may cause an impediment to pulmonary venous blood flow is that designated as cor triatriatum, triatrial heart or congenital stenosis of the common pulmonary vein.[54–57] In this condition the pulmonary veins enter an accessory cardiac chamber. The latter is connected by an opening with the left atrium. Otherwise the heart is normally formed. If the opening between the accessory cardiac chamber and the true left atrium is small, as is usually the case, symptoms and secondary effects indistinguishable from those of mitral stenosis occur. Cor triatriatum is another condition in which clinical recognition may set the stage for surgical intervention with enlargement of the small opening between the accessory chamber and the true left atrium, thus relieving the obstruction to pulmonary venous flow.

Conditions Associated with Excess Pulmonary Blood Flow without Elevation of Pulmonary Venous Pressure. So far we have been concerned with conditions in which the consequences of elevated pulmonary venous pressure may give rise to the paramount symptoms. Cyanosis and oxygen desaturation of the systemic arterial blood are not present in these conditions unless pulmonary complications become manifest.

There are other conditions which likewise do not have cyanosis or oxygen desaturation of the systemic arterial blood and in which pulmonary symptoms may result. In the latter group of cases the pulmonary symptoms need not be associated with elevated pulmonary venous pressure, but the pulmonary complications result from the effects of excess pulmonary flow. In this group pulmonary complications are usually manifest as congestion and hemorrhage. The latter conditions are represented generally by atrial septal defects with or without valvular abnormalities.

ATRIAL SEPTAL DEFECT. The ordinary type of atrial septal defect represents incompetence of the valve of the foramen ovale. Usually patients with this malformation pass through periods during which they are observed by the pediatrician without any outward serious manifestations. Frequently such patients are not recognized as having a cardiac abnormality until adult life, when congestive heart failure, cerebral abscess or paradoxic embolism, representing the most frequent complications, become manifest.

Some infants and children may show deficient degrees of body growth, and less commonly death during this period may occur from pulmonary hemorrhage representing a complication of excess pulmonary flow.[58]

ATRIAL SEPTAL DEFECT AND MITRAL STENOSIS. The combination of atrial septal defect and mitral stenosis is at times called the *Lutembacher syn-*

drome. Though the mitral stenosis may be congenital, it is more frequently rheumatic in origin. A frequently expressed misconception is that the Lutembacher syndrome is common, when in fact it is rare.

The functional disturbances of the Lutembacher syndrome are similar to those of atrial septal defect, pulmonary recirculation being the major disturbance. On hypothetical grounds the patient with atrial septal defect and mitral stenosis has the basis for a greater degree of pulmonary recirculation than a patient with an atrial septal defect and a normal mitral valve.

In a patient with mitral stenosis and an intact atrial septum the left atrial pressure and pulmonary venous pressure are elevated. When the patient with mitral stenosis also has an atrial septal defect, the left atrial and pulmonary venous pressures do not become elevated unless the right ventricle fails.

DEFECT OF THE LOWER ATRIAL SEPTUM AND DEFORMITY OF THE ATRIOVENTRICULAR VALVES. There is a pathologic complex in which a defect of the lower portion of the atrial septum is associated with deformity of the mitral or both atrioventricular valves. This complex may be termed *persistent common atrioventricular canal*.[59] When the mitral valve is the only valve deformed, the condition may be said to be present in the partial form. When both mitral and tricuspid valves are involved, the condition may be considered to represent the complete form of persistent common atrioventricular canal.

In the partial form, in addition to a defect in the lower portion of the atrial septum, there is a cleft in the anterior leaflet of the mitral valve, while the tricuspid valve is normal. Such hearts usually are found in patients dying during adult life most commonly of congestive cardiac failure and less frequently of bacterial endocarditis of the deformed mitral valve.

As for functional disturbances in this form of the malformation, the usual characteristics of atrial septal defect exist: that is, a left-to-right shunt at atrial level. There may also be mitral insufficiency resulting from the cleft in the anterior mitral leaflet.

In the complete form of persistent atrioventricular canal there is a defect in the lower portion of the atrial septum, and the atrioventricular valvular tissue is represented by one valve common to both sides of the heart. When the heart is viewed in a conventional manner, there appear to be clefts both in the septal leaflet of the tricuspid valve and in the anterior leaflet of the mitral valve. The pathologic evidence conforms to the clinical deduction that in the complete form of the condition there is greatly excess pulmonary blood flow. This probably results from the presence of the atrial septal defect coupled with insufficiency of the common atrioventricular valve. Death under one year of age is common and usually results from pulmonary congestion and hemorrhage. Mongolism is commonly but not invariably associated with the complete form.

COMMUNICATION OF THE CORONARY SINUS WITH THE LEFT ATRIUM. In about 25 per cent of normal hearts there are grossly visible openings in the left atrial wall a short distance from the mitral valve. These usually measure about 1 mm. in diameter. By injection methods it is possible to demonstrate that these openings represent the left atrial ostia of channels which connect the left atrium with the coronary sinus. Normally, no recognizable functional disturbance results from these small communications.

In an unusual specimen reported by Dr. Joseph D. Craig[60] from a 5 month old male infant, the left atrial opening of one of such channels was large, measuring about 1 cm. in diameter. Thus there was a direct and gross connection between the left atrium and the coronary sinus (Fig. 8). The excess pulmonary blood flow from

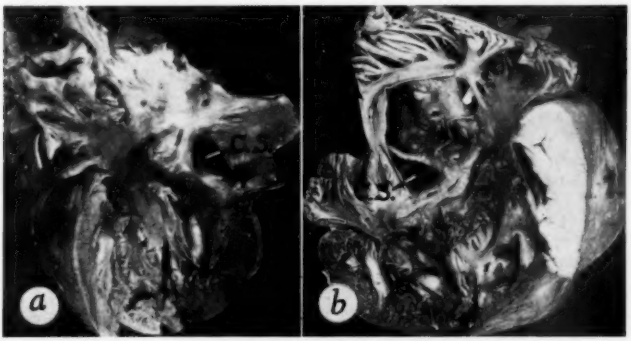

Fig. 8. Anomalously large connection between coronary sinus and left atrium in the 5 month old male infant described by Craig.[60] *a*, Left side of heart. Above the mitral valve there is an anomalously large opening (*C.S.*) representing communication between the left atrium and the coronary sinus. *b*, Right side of heart. The coronary sinus (*C.S.*) enters the right atrium normally. Probe in superior vena cava. The abnormally large connection between the coronary sinus and the left atrium created a functional disturbance like that in atrial septal defect.

which the patient suffered is to be attributed to blood flow from the left atrium to the coronary sinus and from the latter into the right atrium. Thus, though the atrial septum was normal, the abnormal channel described had the identical significant functional effects as though an atrial septum existed.

PARTIAL ANOMALOUS PULMONARY VENOUS CONNECTION. Anomalous connection of the pulmonary veins with the right atrium or one of its tributary veins may involve all or only part of the pulmonary tissue, the remainder having normal venous connection with the left atrium. Since total anomalous pulmonary venous connection is associated with incomplete saturation of the hemoglobin in the systemic arterial blood, this condition does not apply in this section of the discussion.

Partial anomalous pulmonary venous connection is not associated with a right-to-left shunt. The function disturbances of partial anomalous pulmonary venous connection are similar to those of atrial septal defect, and

the two conditions may have similar clinical pictures and secondary pathologic effects. In partial anomalous pulmonary venous connection survival to adult life is usual, and many patients do not have symptoms of the condition unless more than half of the pulmonary tissue drains into the right side of the heart.[61-63]

Dyspnea on Exertion

A small number of "acyanotic" conditions exist in which cardiac failure may result, but pulmonary edema does not necessarily occur. These conditions are premature closure of the foramen ovale, pericardial defect and pulmonary valvular stenosis with intact atrial and ventricular septa, so-called isolated pulmonary stenosis.

PREMATURE CLOSURE OF THE FORAMEN OVALE. In the fetus the foramen ovale is a channel through which some of the blood returning to the heart by way of the inferior vena cava is carried into the left atrium. Though this channel is put out of use shortly after birth, it represents an important avenue of blood flow before birth. Support of this concept comes from evidence supplied by the rare case in which the foramen ovale is closed before birth. In these cases, there is obligatory flow of all the inferior caval blood into the right side of the heart. The right atrium and ventricle are dilated and hypertrophied, while the left side of the heart is underdeveloped.

Premature closure of the foramen ovale may be responsible for right ventricular failure occurring before birth,[64] some of the infants being born with edema and severe effusions. Other infants may appear well at birth and severe cardiac failure develop within several days of birth.[65, 66] In some this is due to right ventricular failure, while in others the underdevelopment of the left side of the heart is responsible for an impediment to pulmonary venous flow. Under the latter circumstances pulmonary edema occurs.

PERICARDIAL DEFECT. As a rule, defects of the pericardium cause no abnormalities in cardiac function and are discovered incidentally either at necropsy or at operation for some condition unrelated to the heart.

The entire pericardium may be absent, or there may be a defect involving only part of this structure. Usually it occurs on the left side, much less commonly on the right.[67]

Difficulties may arise from strangulation of the heart when part of it becomes herniated through the defect.

In a specimen which Dr. L. A. Stapley submitted from a stillborn male infant, a part of the right ventricle and right atrium had herniated through the defect (Fig. 9).

ISOLATED PULMONARY VALVULAR STENOSIS. In isolated pulmonary valvular stenosis there is stenosis at the pulmonary valve, while the ventricular and atrial septa are closed. No shunt is possible. All the blood flowing

through the heart must pass through the stenotic pulmonary valve. Since the cardiac output is normal, unless cardiac failure is present,[68-73] the flow is accomplished with an expenditure of considerable work by the right ventricle. A consequence is pronounced right ventricular hypertrophy. The wall of the right ventricle may exceed in thickness that of the left ventricle, which is normal. The hypertrophy of the right ventricular wall is concentric, occurring at the expense in size of the right ventricular chamber. In the outflow portion of the right ventricle the encroachment upon the chamber by the hypertrophic wall may, in some cases, be responsible for secondary foci of the obstruction beneath the pulmonary

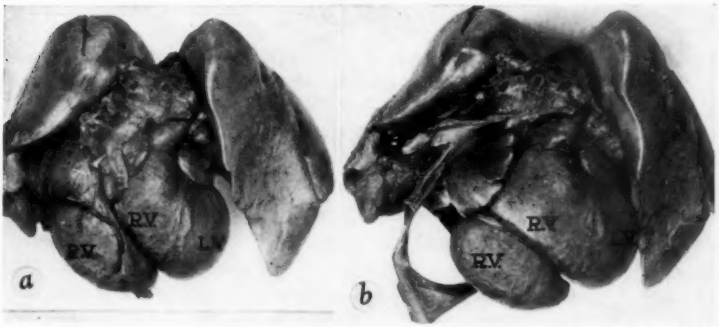

Fig. 9. Heart and lungs in a stillborn male infant in whom a portion of the right ventricle herniated through a pericardial defect. Specimen submitted by Dr. L. A. Stapley. *a*, The heart and lungs from in front. The left side of the pericardium has been removed, leaving only that part on the right through which a portion of the right ventricle herniated. *R.V.*, right ventricle; *L.V.*, left ventricle. *b*, Specimen oriented as in *a*, but with constricting collar of pericardial defect removed from the heart and displaced to the right (left side of illustration). The constriction in the right ventricle created by the defect is apparent.

valve.[74, 75] Under these circumstances the infundibular obstruction occurs over some distance, the upper limits of its length being the length of the outflow portion of the right ventricle (Fig. 10, *a* and *b*).

Though some patients with isolated pulmonary valvular stenosis may enjoy relative well-being for many years, complications may occur in infants and children. Two major ones are right ventricular failure and bacterial endocarditis. The foci of infection may originate in one of three areas: the tricuspid valve, the pulmonary valve or the region of the bifurcation of the pulmonary trunk that is traumatized by the jetlike stream of blood striking this area after passing through the stenotic pulmonary valve.

INFUNDIBULAR OSTIAL STENOSIS. In an unusual case there appears a fibrous collar in the entrance to the outflow tract of the right ventricle (Fig. 10, *c*). The opening in the collar is usually small enough to act as a significant barrier to the emptying of the right ventricle. In some cases

this condition is associated with a ventricular septal defect[67]; under these circumstances the functional disturbances are not unlike those of the tetralogy of Fallot with relatively mild pulmonary stenosis.

In the cases that do not have an associated ventricular septal defect the secondary effects and functional disturbances are almost identical with

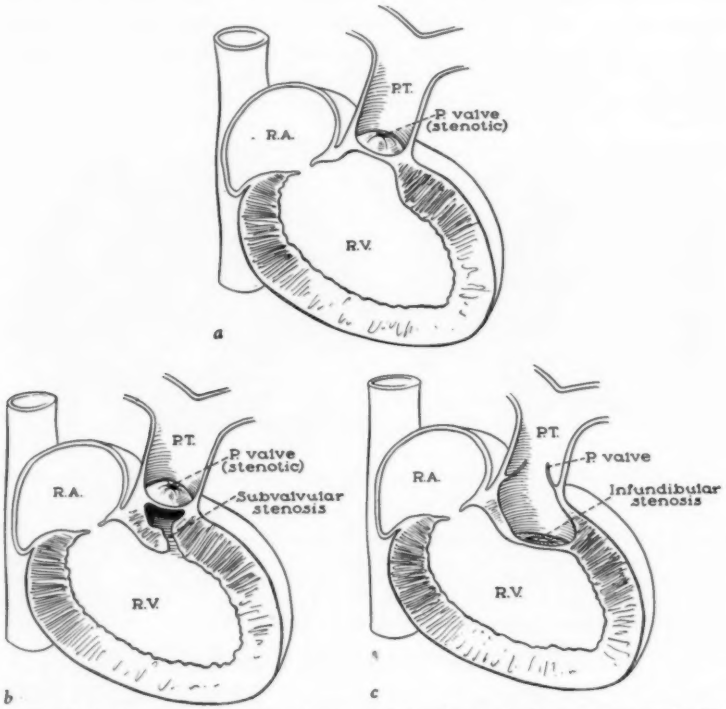

Fig. 10. Anatomic variations in pulmonary obstruction in "pulmonary stenosis" with intact ventricular septum. *a*, Pulmonary valvular stenosis. *b*, Pulmonary valvular stenosis with associated infundibular stenosis. *c*, Stenosis of the infundibular ostium with normal pulmonary valve.

those in isolated pulmonary valvular stenosis.[77, 78] In the latter type of case the heart shows a normal pulmonary valve, and the outflow tract of the right ventricle is of normal thickness. Proximal to the zone of obstruction the right ventricular wall is hypertrophied.

PERSISTENT CYANOSIS

In congenital cardiac disease, cyanosis, exclusive of its appearance during periods of cardiac failure, results from the entry of systemic venous

blood into the left side of the heart or into the aorta. The cyanosis therefore is a manifestation of incomplete saturation of the hemoglobin within the systemic arterial system.

With the exception of a few conditions, the cyanotic forms of congenital cardiac disease are associated with right ventricular hypertension, functionally, and with right ventricular hypertrophy, anatomically. In a clinical case of cyanotic congenital cardiac disease, evidence that right ventricular hypertrophy is lacking immediately suggests that an unusual type of malformation is the basis of the problem. Conditions that come into this category will be discussed after the commoner types of cyanotic congenital cardiac malformations have been presented.

Cyanotic Forms of Congenital Cardiac Malformation Associated with Right Ventricular Hypertrophy

PULMONARY VALVULAR STENOSIS WITH INTACT VENTRICULAR SEPTUM AND WITH ATRIAL SEPTAL DEFECT. In isolated pulmonary valvular stenosis there is no opening in either the ventricular or the atrial septum. In somewhat more than half of the cases in which there is pulmonary valvular stenosis with an intact ventricular septum, the atrial septum has some sort of defect. The latter type of case concerns us at this point, since these patients may be cyanotic on the basis of a right-to-left shunt through the opening in the atrial septum.[68–73, 79]

The atrial septal defect usually takes the form of a probe patency. The channel of the foramen ovale allows flow from right to left, but not in the reverse direction. In some cases there may be true defects of the atrial septum, additionally, but they are usually small.

Except for the differences in appearance of the atrial septum, the heart in isolated pulmonary stenosis does not differ from that in cases with an opening in the atrial septum and with a pulmonary valvular stenosis and intact ventricular septum. In the exceptional case of Wood,[80] the left ventricle was enlarged.

In cases with an atrial septal defect the complications are the same as those of isolated pulmonary stenosis; in addition, cerebral abscess may be seen in cases with an associated atrial septal defect.

Cases with a Common Ventricular Ejectile Force for the Systemic and the Pulmonary Circulations. In most cases with right ventricular hypertrophy and cyanotic congenital cardiac disease the right ventricle assumes the dual function of propelling blood to the pulmonary arterial and to the systemic arterial circulations. The right ventricle builds up pressure equivalent to aortic pressure and in this way exerts pressure of similar magnitude to that of the left ventricle.[81] Such a circumstance is normal in the normal fetus, wherein the right ventricle supplies blood to the descending aorta by way of the ductus arteriosus.[82] When the right ventricle

continues such a dual function after birth, because of malformations, it maintains, as in the normal fetus, a thickness similar to that of the left ventricle.

With the right ventricle supplying both the lesser and greater circulations and exerting systolic pressures equal to systemic systolic pressure, there must be some obstruction to pulmonary flow in order for such a build-up of pressure to occur. In some cases this obstruction occurs in the major pathways to the lungs, as in the pulmonary trunk, at the pulmonary valve or in the subpulmonary outflow tract of the right ventricle.

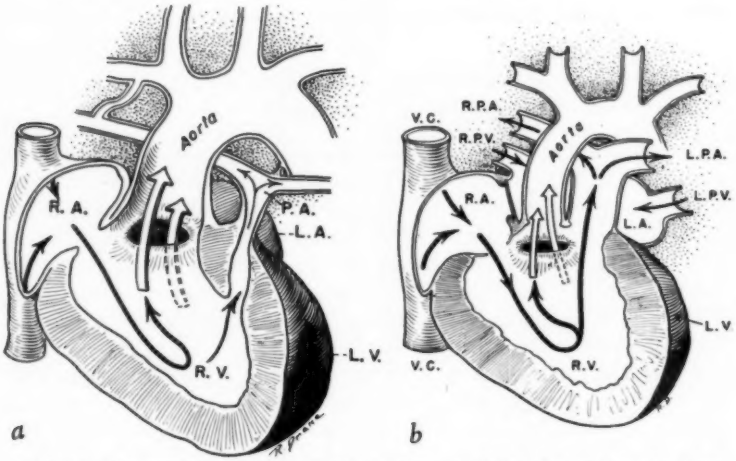

Fig. 11. The central circulation in the tetralogy of Fallot (*a*) and in the Eisenmenger complex (*b*). (*a*, From Dry and associates: Congenital Anomalies of the Heart and Great Vessels. A Clinicopathologic Study of 132 Cases. Postgrad. Med., Vol. 4. Reproduced with permission. *b*, From J. E. Edwards.[74] Reproduced with permission of the American Medical Association.)

In other cases the obstruction to pulmonary flow occurs in the muscular arteries within the lung.[83, 84]

TETRALOGY OF FALLOT. The tetralogy of Fallot is a good example of a condition in which the right ventricle supplies blood to both circulations and in which there is a barrier in the major pathway to the lung (Fig. 11, *a*). The aorta arises from both ventricles above a ventricular septal defect. The right ventricle, being of about the same thickness as the left, is considered hypertrophied. The commonest site of obstruction to pulmonary blood flow is in the subpulmonary portion of the right ventricle, where there is a muscular-walled tract usually of narrow caliber. Less common sites of obstruction are the pulmonary valve or pulmonary trunk. Either structure may represent a barrier to pulmonary blood flow because it is either stenotic or atretic.[85, 86]

Though the right ventricular pressure is at elevated and systemic levels, the barrier between this chamber and the pulmonary arteries is responsible for a significantly lower systolic pressure in the pulmonary arteries than in the right ventricle. In actual measurements the pressures in the pulmonary arteries in the tetralogy of Fallot are within normal levels or below normal.

In this condition thrombotic lesions within the small arteries and arterioles of the lungs have been described, but these observations do not gainsay the basically normal structure of the components of the small pulmonary vessels in the tetralogy of Fallot.

The association of a right aortic arch is a common condition occurring in about 20 per cent of the cases. Usually when a right aortic arch occurs under these conditions, the descending aorta is on the right also, except in the lower part of the thorax, where it crosses behind the esophagus to enter the abdomen through the aortic hiatus of the diaphragm. The branches of the right aortic arch in cases with the tetralogy are usually disposed as a mirror image of the normal, the first branch being a left innominate artery from which the left common carotid and left subclavian arteries arise. The second and third branches of the aorta are the right common carotid and right subclavian arteries, in that order from before backward. An aortic arch of the type described does not cause symptoms of tracheal or esophageal compression, but in exceptional cases with a right aortic arch there may be undue compression of these tubes leading to dysphagia or evidence of tracheal obstruction. The commonest significant variant of this type of the right aortic arch described is the one in which the first branch of the arch is the left common carotid artery rather than a left innominate artery. The left subclavian artery arises as the fourth branch of the right aortic arch and passes behind the esophagus to proceed to the left side of the body. In a case of this type which we observed a left ligamentum arteriosum inserted into the left subclavian artery on the left of the midline, thus causing a true "vascular ring."

The complications of the tetralogy of Fallot include congestive cardiac failure, right-sided bacterial endocarditis, cerebral abscess and cerebral infarction. Not infrequently, however, the pathologist cannot find anatomic evidence of these complications, and the history is one of gradually increasing degrees of intense cyanosis leading gradually to death, or of death occurring during an attack of intensified cyanosis and syncope.

Such cases, relatively common among patients on whom operation is not performed, represent examples of severe obstruction to pulmonary blood flow. In some there is pulmonary atresia or severe stenosis with evidence of recent closure of the ductus arteriosus. In others the evidence more commonly suggests that the size of the tract leading to the pulmonary arteries changes little with growth of the body. A tract which may have carried sufficient blood for maintenance of life when the body was

small becomes insufficient as the body grows and the blood volume increases. In some cases there is the added factor of narrowing of the subpulmonary tract by deposition of endocardial fibrous tissue in this region as a reaction to the traumatic effects of the currents of blood expressed through a narrow opening (Fig. 12). The tetralogy of Fallot is the commonest type of malformation in which cerebral abscess is a complicating lesion.

EISENMENGER COMPLEX. Another condition shares with the tetralogy of Fallot the characteristics of biventricular origin of the aorta above a

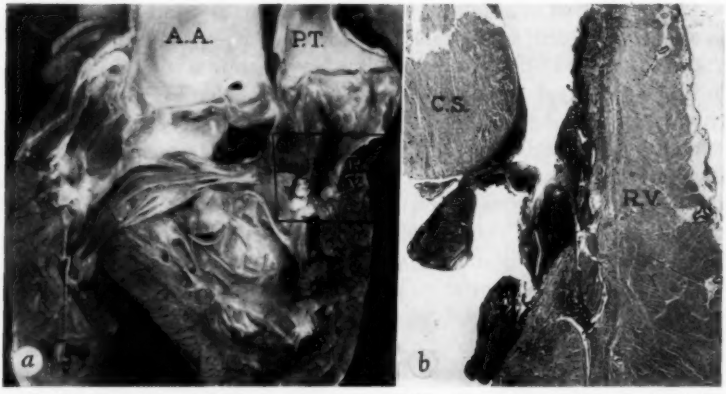

Fig. 12. Tetralogy of Fallot in a woman aged 25 years. *a*, Gross photograph of the right ventricle showing origin of the aorta (A.A.) above a ventricular septal defect. Beneath the pulmonary valve there is a narrow infundibular tract between the crista supraventricularis (*C.S.*) behind and the anterior wall of the right ventricle (*R.V.*) in front. At the entrance of the subpulmonary tract (within rectangle) there is considerable fibrous endocardial thickening. *P.T.*, Pulmonary trunk. *b*, Photomicrograph of region illustrated within rectangle in *a*. The pronounced endocardial thickening adds to the narrow state of the tract in this region. (Verhoeff's elastic tissue stain and counterstained with van Gieson's connective tissue stain; × 4).

ventricular septal defect and right ventricular hypertrophy, but, contrariwise, does not exhibit any obstruction in the major pathway to the lungs. This condition is the Eisenmenger complex.

In the Eisenmenger complex there is a defect in the membranous portion of the ventricular system, and the right ventricle readily communicates with the aorta. The major pathway to the lungs is not narrow. On the contrary, it may be normal or even wider than normal. Yet with these anatomic arrangements the right ventricle exerts systolic pressures like those of the left ventricle, and the right ventricle propels some venous blood to the aorta. These functional characteristics can exist only with a high degree of resistance to pulmonary flow (Fig. 11, *b*). Functional studies in living patients with this complex have revealed that there is an

abnormally high resistance to flow through the pulmonary "arteriolar" bed.[87]

Microscopic studies of the lungs from similar cases reveal abnormally thick medial layers of the muscular arteries, while the next class of vessel, the arteriole, is normal.[83, 88] Probably the high pulmonary "arteriolar" resistance in the Eisenmenger complex occurs at the level of the muscular arteries. The thick media in this type of vessel has been regarded as maintenance of fetal structural characteristics. In the fetus the muscular ar-

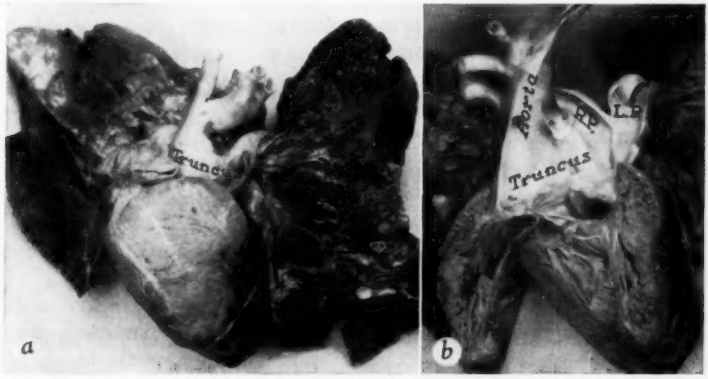

Fig. 13. Persistent truncus arteriosus with wide pulmonary arteries in a male infant 2 months of age. *a*, Heart and lungs from in front. A single vessel representing a persistent truncus arteriosus (*Truncus*) emerges from the heart and divides into the aorta and a short pulmonary trunk. The lungs showed congestion, edema and hemorrhages. *b*, The interior of the right ventricle and great vessels. The right ventricular wall is hypertrophied. Above a membranous ventricular septal defect arises the persistent truncus arteriosus (*Truncus*). The two coronary arteries take origin from this vessel. It then terminates in the aorta and a short pulmonary trunk. From the latter arises wide left (*L.P.*) and right (*R.P.*) pulmonary arteries.

teries normally have thick medial layers. Possibly at the level of these vessels there is a zone of high resistance to flow which makes possible the normal phenomena in the fetus wherein, in the absence of any barrier in the major pathways to the lungs, the right ventricle supplies blood simultaneously to the lungs and to the descending aorta.

PERSISTENT TRUNCUS ARTERIOSUS. Persistent truncus arteriosus is a condition in which only one vessel leaves the heart and from it the coronary, pulmonary and systemic circulations are supplied (Fig. 13). All cases have a defect of the membranous ventricular septum, and the single great arterial vessel, the persistent truncus arteriosus, usually arises from both ventricles above the defect. In a few cases the vessel arises entirely from the right ventricle, and even less often from the left ventricle. Biventricular hypertrophy is the rule. A right aortic arch is common.[89–93]

In some cases the functional disturbances are like those in the Eisen-

menger complex, and in others like those in the tetralogy of Fallot. These disturbances depend upon the size of the pulmonary arteries and the response of the small pulmonary vessels.

In cases with narrow or absent major pulmonary arteries the functional disturbances are like those in the tetralogy of Fallot. When the major pulmonary arteries are wide, there is a basis for adequate blood flow. If the pulmonary vessels maintain a high resistance to flow, functional characteristics like those in the Eisenmenger complex exist. If the small pulmonary vessels fail to exert a high resistance to flow, there will be a preferential flow of blood to the lungs, with pulmonary congestion, edema and hemorrhages as the factors leading to pulmonary insufficiency and death.

Symptoms and death during infancy are common.[94] Exceptional patients survive to adult life.[95, 96] These usually have narrow or absent pulmonary arteries.

COR TRILOCULARE BIATRIATUM. In cor triloculare biatriatum there is a single ventricle. There are two atria and two atrioventricular valves. The great vessels are in a transposed position; that is, the aorta arises anterior to the pulmonary trunk, and the two run parallel.

Whether a case functionally resembles the tetralogy of Fallot or the Eisenmenger complex will depend principally upon the structure of the heart. In a few cases there is asociated pulmonary stenosis, the functional disturbances being like those in the tetralogy. More commonly the pulmonary trunk is wide and there is no barrier in the pathway to this vessel.[97] In addition, the peculiar orientation of the ventricular muscles commonly creates a zone of subaortic narrowing. Under these conditions, if the small pulmonary vessels exert no excess resistance to flow, there are excess pulmonary flow and eventually fatal pulmonary complications.

Those patients who have the type of heart under discussion and survive to childhood or adult life do so on the basis of high resistance to pulmonary flow. Functionally, such cases closely resemble cases of the Eisenmenger complex. Microscopic study of the small pulmonary vessels reveals changes identical to those seen in the Eisenmenger complex.[98] Isolated dextrocardia is present in some cases. Deaths from cardiac failure or the effects of excess pulmonary flow are common in infancy, although an occasional patient reaches childhood and a rare one adult life. Cerebral abscess is an occasional complication.

Findings at cardiac catheterization were described by Deuchar,[99] and electrographic observations in 2 cases were reported by Freireich and Nicolson.[100]

COR BILOCULARE. In cor biloculare there is a single atrium, a single ventricle and a single atrioventricular valve.[101] Not infrequently a persistent left superior vena cava is present which empties into the left side

of the common atrium. Under these circumstances there is absence of the coronary sinus.

There are three patterns of arterial connections with the common ventricle. In some cases there is a single vessel representing a persistent truncus arteriosus. The nature and branches of this vessel have variations already discussed under Persistent Truncus Arteriosus. In other cases an aorta and a pulmonary trunk are identifiable, but the great vessels are in transposed relationships, and the pulmonary trunk, which lies behind the aorta, is atretic. Under these circumstances a patent ductus arteriosus carries blood to the pulmonary arteries. The least common arrangement is the one in which patent aortic and pulmonary arterial vessels are present. When the pulmonary trunk is patent, it usually is wide.

The functional derangements in cor biloculare depend largely upon the arterial connections with the ventricle. In cases with narrow or atretic pulmonary arteries there is deficient pulmonary blood flow, a great volume of right-to-left shunt and prominent cyanosis. Cases of this type resemble the tetralogy of Fallot from a functional viewpoint.

In patients who have wide pulmonary arteries there is usually evidence of excess pulmonary blood flow, and death results from the complications of this phenomenon.

Under any circumstances, survival beyond infancy is decidedly uncommon.

TAUSSIG-BING COMPLEX. The malformation designated as the Taussig-Bing complex has some functional characteristics like those of the Eisenmenger complex. Anatomically, it is a variant of complete transposition of the great vessels. The aorta arises from the right ventricle, while the wide pulmonary trunk arises above a ventricular septal defect from both ventricles[102, 103] (Fig. 14). The anatomic arrangement would tend to set the stage for excess pulmonary flow, but there may be essentially normal pulmonary flow[102] brought about by a high resistance to pulmonary blood flow.

PATENT DUCTUS ARTERIOSUS WITH PULMONARY HYPERTENSION. Patent ductus arteriosus without pulmonary hypertension represents a clinicopathologic entity quite different from patent ductus arteriosus with pulmonary hypertension. In the former condition there is no desaturation of the systemic arterial blood, and the condition is properly placed in the category of acyanotic congenital cardiac disease.

When pulmonary hypertension exists, there is right ventricular hypertrophy, while the left ventricle is normal. If the pulmonary arterial pressure is similar to the systemic arterial pressure, there may be a sufficient shunt from right to left to cause cyanosis.[104–113]

Probably two types of background exist among cases of patent ductus arteriosus with pulmonary hypertension. The first is similar to that of the

Eisenmenger complex, in which, after birth, the right ventricle continues to supply blood to the aorta as it did during fetal life. In this case the assumed response on the part of the small pulmonary vessels would be like that in the Eisenmenger complex. Structurally, the vessels are similar.

In another group of cases with patent ductus arteriosus pulmonary hypertension is not present as an initial disturbance, but develops secondarily.

Such a case was presented by Campbell and Hudson, the patient being a 39 year old woman.[109] A continuous murmur typical of uncomplicated patent ductus arteri-

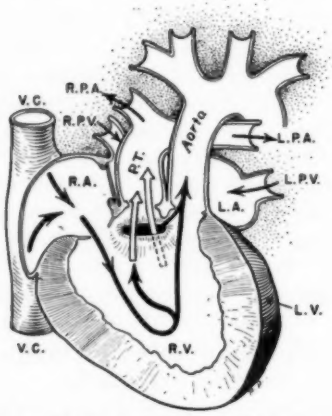

Fig. 14. Intracardiac circulation in the Taussig-Bing complex. (From J. E. Edwards, in Gould's Pathology of the Heart. Springfield, Illinois, Charles C Thomas. With permission.)

osus had been recorded about 10 years before her death from congestive cardiac failure. During the latter months of her life no such murmur was present. Necropsy revealed extensive intimal lesions of the small pulmonary arterial vessels. These evidently had been responsible for high resistance to pulmonary blood flow and for the pulmonary hypertension which was responsible for disappearance of the major part and perhaps all of the left-to-right shunt. In some cases belonging to the latter category, occlusive pulmonary vascular lesions are caused by organized thrombi.[112]

AORTIC ATRESIA, MITRAL ATRESIA, COEXISTENT MITRAL AND AORTIC ATRESIA. In aortic atresia, mitral atresia, or the two conditions coexisting, there is usually a barrier to pulmonary venous flow, and the right or a single ventricle propels a mixture of venous and completely saturated blood to both the systemic and pulmonary arterial circulations.

The barrier to pulmonary venous flow results from absence of a normal outlet for blood from the left side of the heart, represented by the malformation, coupled with a small foramen ovale—the usual channel through which blood escapes from the left side of the heart.

The right atrium receives blood from both the systemic and the pul-

monary veins, the latter by way of the foramen ovale. From the right atrium the blood flows to either a right ventricle or a common ventricle. From a functional viewpoint the right ventricle, when present, functions as a common ventricle.*

The proportion of blood expelled by the anatomic or functional common ventricle to one system and to the other depends to a large extent upon the resistance to pulmonary blood flow (Fig. 15, *a*). Since no pulmonary arterial narrowing is present, it is potentially possible for a great

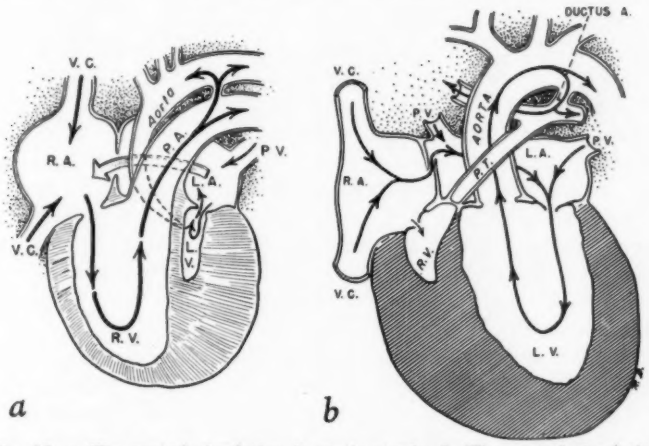

Fig. 15. *a*, The central circulation in aortic atresia. *b*, The central circulation in pulmonary atresia. (*a*, From T. J. Dry and associates: Congenital Anomalies of the Heart and Great Vessels. A Clinicopathologic Study of 132 Cases. Postgrad. Med., Vol. 4. Reproduced with permission. *b*, From J. E. Edwards, in Gould's Pathology of the Heart. Springfield, Illinois, Charles C Thomas, Publisher. With permission.)

volume of blood to flow to the lungs. This phenomenon, coupled with the impediment to pulmonary venous drainage, is responsible for pulmonary edema.

If the small pulmonary arterial vessels create a high resistance to pulmonary blood flow, the pulmonary flow is relatively smaller and the pulmonary bed is spared the hazard of edema. But such a "protective" mechanism has its drawbacks in reducing pulmonary flow and simultaneously causing the major proportion of the blood expelled by the heart to flow to the systemic circulation without the benefit of oxygenation in the lungs.

Obviously persons with these malformations are constantly subjected to the dangers of pulmonary edema and inadequate pulmonary blood flow to supply the oxygen needs of the body. These hazards have their

* In mitral atresia, a common ventricle frequently exists. In aortic atresia and in coexistent aortic and mitral atresia right and left ventricles are usually identifiable.

expression in the frequent deaths in the early neonatal period of patients with either aortic atresia or coexistent aortic and mitral atresia. As a group, patients with mitral atresia live somewhat longer, but survival beyond a few months after birth is uncommon even in this condition.

PULMONARY VALVULAR ATRESIA WITH INTACT VENTRICULAR SEPTUM. When the pulmonary valve is atretic and the ventricular septum is intact, the only outlet for blood entering the right side of the heart is the foramen ovale. The left atrium, therefore, represents a common receiving atrium. Systemic venous and pulmonary venous blood mix here. The mixture enters the left ventricle through the mitral valve. The left ventricle functionally represents a common ventricle. From this chamber, blood is ejected into the aorta. The pulmonary blood supply depends upon flow through the ductus arteriosus from the aorta into the pulmonary artery. This condition is somewhat comparable to aortic atresia in that a common ventricle supplies one circulation directly and the other one indirectly through the ductus arteriosus. In pulmonary valvular atresia the ductus arteriosus is frequently narrow and therefore represents a barrier between the aorta and the pulmonary arteries (Fig. 15, *b*). The pulmonary arterial pressure, therefore, is probably considerably lower than the aortic pressure. In this way pulmonary valvular atresia has a tendency to resemble the tetralogy of Fallot functionally.

In contrast, in aortic atresia and coexistent aortic and mitral atresia the functioning ventricle is the right ventricle, which exerts systemic pressure and at the same time is in free communication with the pulmonary arteries, there being no barrier between the propelling ventricle and the pulmonary arteries. Therefore in aortic atresia there is the chance of excess pulmonary flow and of pulmonary hypertension, making the cases somewhat comparable functionally to the Eisenmenger complex.

The right ventricle in pulmonary valvular atresia with intact ventricular septum usually has a characteristic appearance—a thin chamber and an exceedingly thick wall. This structural peculiarity may depend upon the coexistence of the basic malformation at the pulmonary valve and a competent, though small, tricuspid valve.

We recently observed 2 cases of pulmonary valvular atresia with intact ventricular septum in which the right ventricular chamber was approximately normal in size and the right ventricular wall, though hypertrophied, did not approach in thickness the tremendous hypertrophy usually seen in this condition. The explanation possibly resides in existence of tricuspid insufficiency in these cases.

Complete Transposition of the Great Vessels

The condition designated as complete transposition of the great vessels occurs more commonly in the male than in the female and is characterized by origin of the aorta from the right ventricle and of the pulmonary trunk from the left ventricle (Fig. 16, *a*). Obviously this anatomic arrangement

is a serious deformity, since it causes delivery of systemic venous blood to the aorta. Life after birth is possible only on the basis of some communication between the two circulations. A patent foramen ovale is

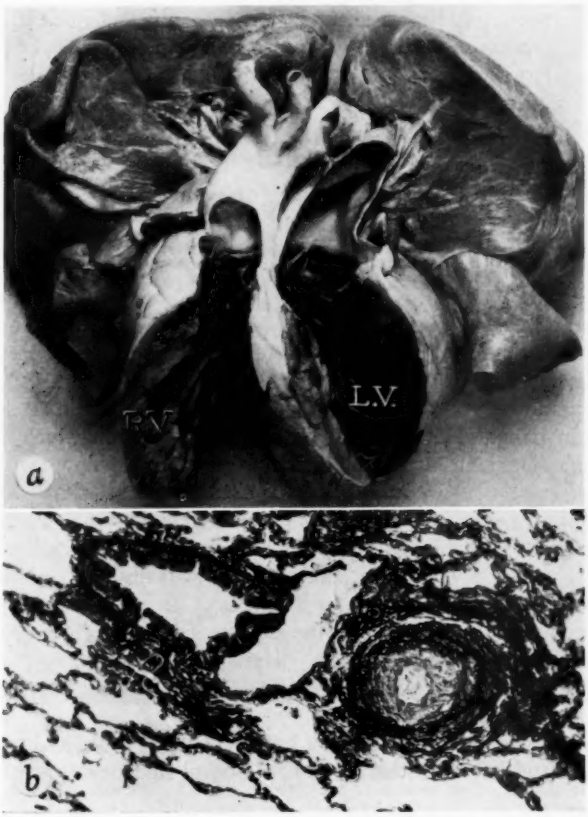

Fig. 16. Complete transposition of the great vessels. From a 5 year old girl. Specimen contributed by Dr. J. D. Barger. *a*, The heart and lungs from in front. The right ventricle (*R.V.*) communicates with the aorta. The left ventricle (*L.V.*) communicates with the pulmonary trunk. There is no pulmonary stenosis. A ventricular septal defect and patent ductus arteriosus were present. *b*, Photomicrograph of the lung in case illustrated in *a*. A muscular artery shows medial hypertrophy and pronounced intimal fibrous proliferation. (Verhoeff's elastic tissue stain and counterstained with van Gieson's connective tissue stain; × 115).

present in most of the cases, a patent ductus arteriosus in about two thirds, and a ventricular septal defect in about half of the cases. Probably in all cases some flow of blood through bronchial arteries, which are noticeably enlarged in some of the patients, allows desaturated blood from the aorta

to flow to the lungs. Fortuitous presence of anomalous pulmonary venous connection is beneficial in that blood saturated with oxygen is carried to the right side of the heart, from which it is delivered to the aorta.[114]

Complete transposition of the great vessels occurs more commonly than was previously supposed. Cyanosis is usually evident at birth, and the condition causes death at an early age. The majority of the patients die when less than six months of age, although in isolated instances survival to adolescence or adult life occurs.

Hanlon and Blalock[115] emphasized that the greater the number and the size of the defects which allow communication between the two sides of the heart, the greater the chances for survival.

The direction of flow through the associated defects varies from one time to another as one of the two circulations becomes overloaded with blood while the other is depleted of blood.[116]

In keeping with this concept is the observation that in complete transposition of the great vessels without pulmonary stenosis, the pulmonary vascular markings may be increased, a significant feature whereby this condition may be distinguished from the tetralogy of Fallot.[117]

Keith and associates[118] found frequent cyclic variation in arterial saturation in patients with this condition, an observation which supports Taussig's statement regarding changing directions of flow through the defects.

The right ventricular pressure is elevated above normal, being at systemic levels. Probably in the absence of associated pulmonary stenosis there is pulmonary hypertension, but it is still unsettled whether the pulmonary arterial pressure, though high, is of the same magnitude as the systemic arterial pressure. That the two are equal is likely in cases with associated large ventricular septal defects. Such cases show pulmonary vascular changes indistinguishable from those in the Eisenmenger complex (Fig. 16, *b*).

The heart shows hypertrophy of both ventricular walls, and frequently the right and left ventricles are of about equal thickness.

Total Anomalous Pulmonary Venous Connection

In the presence of an otherwise normally formed cardiovascular system, connection of all the pulmonary veins with the right atrium or a tributary vein of this chamber instead of with the left atrium is a serious disorder (Fig. 17).

All the blood returning to the heart enters the right atrium. The left side of the heart and the systemic circulation depend upon an atrial septal defect or a probe-patent foramen ovale as the only avenue of ingress of blood.

Probably the pulmonary blood flow is greater than the systemic blood

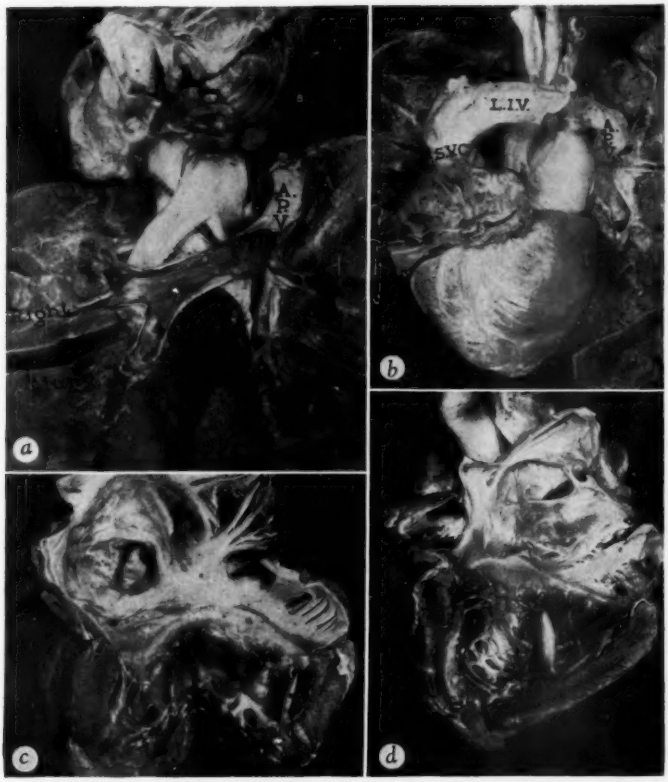

Fig. 17. Total anomalous pulmonary venous connection with the left innominate vein. From a 3 month old patient. Specimen contributed by Dr. J. D. Barger. *a*, The lungs from in front. The heart has been reflected upward. The pulmonary veins do not connect directly with the heart. A conjoined vein from the right lung crosses the midline and fuses with a similiar vein from the left lung to give rise to a venous stem which runs vertically anterior to the root of the left lung. This anomalous vertically directed venous trunk (*A.P.V.*) terminates in the left innominate vein, as illustrated in *b*. The vertically directed anomalous pulmonary vein is not to be considered a persistent left superior vena cava, although in the literature such a structure has been so called. *b*, The anomalous vein (*A.P.V.*) formed by union of all the pulmonary veins joins the left innominate vein (*L.I.V.*), from which blood is carried into the right atrium by way of the superior vena cava (*S.V.C.*). *c*, Right side of heart: right ventricular hypertrophy, dilatation of right atrium, patent foramen ovale. *d*, Left side of heart: left atrium and left ventricle somewhat smaller than normal. The patent foramen ovale represents the route by which blood flows into the left atrium.

flow in all cases, as evidenced by functional studies and by the pathologic observation that the right ventricle is considerably larger than normal, while the left atrium and ventricle are smaller than normal.

All the blood distributed to the pulmonary and to the systemic circulations is first pooled and mixed in the right atrium. The level of oxygen saturation in the systemic arteries, therefore, is of essentially the same level as it is in the right atrium.[119, 120]

In total anomalous connection of the pulmonary veins there are both left-to-right and right-to-left shunts. Death during infancy is common, usually the result of desaturation of the systemic arterial blood coupled with deficient systemic flow.[61–63]

In cases with associated large atrial septal defects the systemic flow is larger and the availability of oxygen to the tissues is greater than in cases with small atrial septal defects. Such cases are probably the exceptional ones that allow some patients to live to adult life.

Cyanosis with Absent Right Ventricle or with no Right Ventricular Hypertrophy

TRICUSPID ATRESIA. "Absence of the right ventricle" is a feature in tricuspid atresia. In the strict sense of the word, only part of the right ventricle is absent, while its outflow portion is identifiable except in the cases in which a single ventricle exists. The clinical features are those of left ventricular hypertrophy, and during cardiac catheterization a right ventricle cannot be entered.

In all cases an atrial septal defect is the only route by which right atrial blood can escape. From this chamber venous blood flows into and mixes with saturated blood in the left atrium. The mixture enters the left or a common ventricle through the mitral valve and is then distributed to the pulmonary and systemic arterial circulations. In some cases there is pulmonary or subpulmonary stenosis, the condition functioning like the tetralogy of Fallot. In other cases there is no pulmonary stenosis and the cases are comparable to the Eisenmenger complex or ventricular septal defect.[121] Usually the latter applies, excessive blood flowing to the lungs and being responsible for complications leading to pulmonary insufficiency (Fig. 18). In the cases without pulmonary stenosis and in which the pulmonary vessels maintain a high level of resistance to flow, the pulmonary arterial pressure is elevated. There is a balanced flow and, as in the Eisenmenger complex, no excess in pulmonary flow.

In only rare cases does tricuspid atresia allow the patient to survive beyond infancy or early childhood. Those patients with this condition who have been reported to have lived longest have had pulmonary or subpulmonary stenosis.

EBSTEIN'S MALFORMATION OF THE TRICUSPID VALVE. Though clinically in

Ebstein's malformation the evidence may suggest right ventricular hypertrophy, the pathologic specimens of this condition show the right ventricle to be either of normal thickness or thin. Usually it is thin and dilated.

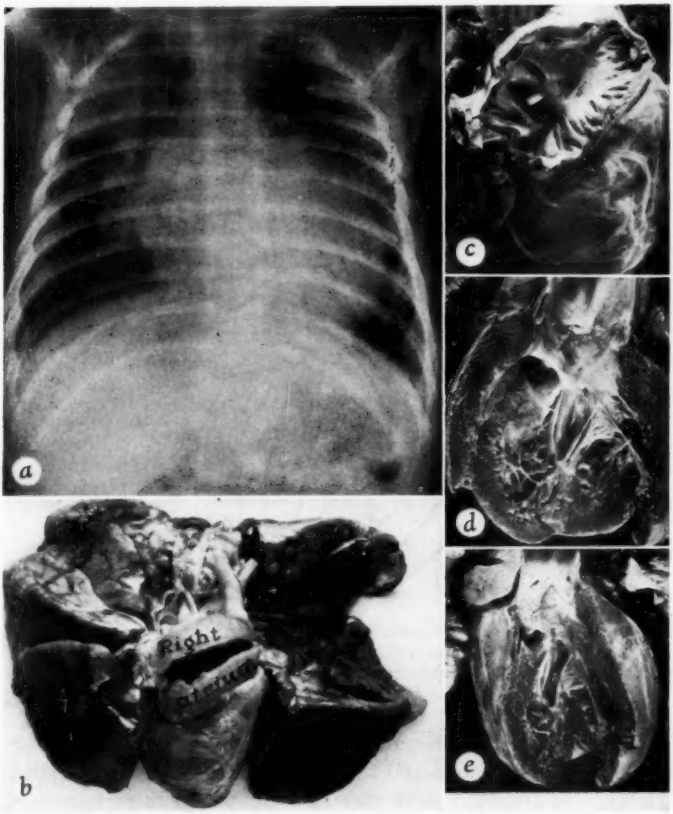

Fig. 18. Tricsupid atresia with wide pulmonary arteries in a male infant dying at the age of 7 weeks from the effects of excess pulmonary flow. *a*, Roentgenogram of the thorax. *b*, Lungs from in front; right lateral view of heart; dilated right atrium; hemorrhagic lesions in lungs. *c*, Interior of right atrium; absence of tricuspid orifice. Probe in patent foramen ovale, which was the only outlet for blood from the right atrium. *d*, The common ventricle and the wide pulmonary trunk. Inferior to the pulmonary valve is the tract leading to the subaortic portion of the outflow tract of the common ventricle. *e*, The aorta arising from the common ventricle.

Functional studies show normal right ventricular and pulmonary pressures.[122–127]

The tricuspid valve is deformed in such a way that its septal and pos-

terior leaflets are attached, not to the annulus fibrosus, but rather to the apical part of the right ventricle.[122, 128] These abnormal valvular attachments make the inflow portion of the right ventricle share in forming a large common receiving chamber with the right atrium, while the only propelling part of the right ventricle is beyond the valve and corresponds mainly to the anatomic outflow portion of the right ventricle.

The basic deformities of the heart in Ebstein's malformation are not responsible for a shunt, but in most cases an atrial septal defect is present.

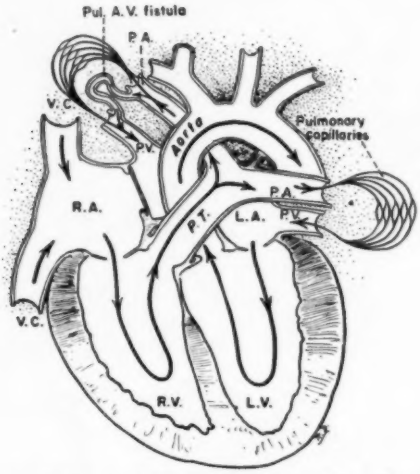

Fig. 19. Diagrammatic representation of the intracardiac and pulmonary circulation in pulmonary arteriovenous fistula of the right lung. (From Jesse Edwards et al.: An Atlas of Congenital Anomalies of the Heart and Great Vessels. Springfield, Illinois, Charles C Thomas, Publisher. 1953. Reproduced with permission.)

Through this defect there is a right-to-left shunt accounting for the systemic arterial desaturation and frequent cyanosis present in this disease.

Though the tricuspid valve may be incompetent in certain cases, in others the normal anterior leaflet appears to guard the orifice adequately.

Survival to adult life is common. Death from anoxia occurs at times. The commonest cause of death is congestive cardiac failure. Cerebral abscess was a fatal complication in 2 of the approximately 30 cases reported with necropsy studies.[129]

ANOMALOUS CONNECTION OF A PERSISTENT LEFT SUPERIOR VENA CAVA WITH THE LEFT ATRIUM. Though rare, a type of congenital cyanotic cardiac disease in which there is no right ventricular hypertension is a condition wherein a persistent left superior vena cava joins the left atrium. In the usual instance of a persistent left superior vena cava, the vein terminates in the coronary sinus and its blood is carried to the right atrium. Under

these conditions no functional disturbance occurs. When the vein joins the left atrium, venous blood carried to the left atrium is responsible for oxygen desaturation of the systemic arterial blood.[130] This possibility is well to bear in mind in congenital cyanosis with evidence of a normal right ventricle. Cure may be expected by division of the anomalous vein.

PULMONARY ARTERIOVENOUS FISTULA. Another congenital condition that may be responsible for cyanosis in the presence of a normal heart is a pulmonary arteriovenous fistula. Venous blood in pulmonary arteries is directed into pulmonary veins without flow through pulmonary capillaries (Fig. 19).

Resection of the involved portion of the lung may return the patient from one debilitated by cyanosis to normality.[131-134]

The frequent association of this condition with familial telangiectasis is established.[135, 136] Multiple pulmonary lesions may occur.[137, 138] Cerebral abscess in the absence of infection of the fistula may occur in some cases.[139] Bacterial infection of the fistula itself has been described by Maier and associates.[140]

Limitations of space make it necessary to omit the references here. They will appear, however, in the author's reprints.

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THE ELECTROCARDIOGRAM IN CONGENITAL MALFORMATIONS OF THE HEART

ROBERT A. MILLER, M.D.

The electrocardiogram has become an established part of the diagnostic process in congenital heart disease. Though an anatomically accurate diagnosis rarely can be made from the electrocardiogram alone in the sense that it may in an acute anterior wall myocardial infarction, information almost as specific may be obtained when the electrocardiogram is correlated with the physical examination and x-ray findings. In a cyanotic infant with a normal-sized heart, a systolic murmur at the base and decreased vascularity of the lung fields, the finding of a left heart strain pattern is practically specific for tricuspid atresia. A right heart strain in the same infant is almost as specific for tetralogy of Fallot. In this manner the clinician is able to derive specific and dependable clinical information, utilizing a few commonly recurring electrocardiographic patterns.

The following discussion is based on the electrocardiograms obtained from approximately 1000 cases of congenital heart disease in which the diagnosis was proved by surgery or postmortem examination. This has been supplemented by unoperated cases, mostly septal defects, in which the diagnosis was established by clinical and laboratory methods. The distribution of proved cases is as follows: tetralogy of Fallot, 400; pulmonary stenosis with intact ventricular septum, 40; tricuspid atresia, 21; coarctation of the aorta, 40; patent ductus arteriosus, 260; isolated dextrocardia and levocardia, 39; postmortem specimens, 200.

From the Children's Memorial Hospital, Chicago.

THE NORMAL ELECTROCARDIOGRAM

The electrocardiogram of infants and children, especially during the first five years of life, shows an evolution from the infantile to the normal adult pattern.[1, 2] Since the diagnosis of right heart strain depends primarily on the right-sided chest leads and aV_R, the following observations are pertinent. A tall R wave is commonly seen in the normal lead aV_R in the first week of life, and then decreases in amplitude from one week to three months of age. A significant R wave is still common up to eighteen months; though the tendency to the adult pattern of a QS begins to appear at approximately two years, an RS pattern is often seen in normal five year olds.

In the first three months of life lead V_{4R} normally may consist of a completely upright complex, and the R/S ratio approaches infinity. From three months on the R wave becomes progressively smaller and the S wave deeper, so that from one to three years of age the R and S waves tend to equal each other. Between three and five years of age the S wave becomes consistently deeper than the R wave is tall.

RIGHT HEART STRAIN

The "Wilson phenomenon," progressive increase in the depth of the S wave, and decrease in the height of the R wave as the electrode moves from V_4R through V_6, is usually not seen in normal children beyond the first week of life, and has been a consistent and helpful component of the diagnosis of right heart strain, especially in infants, in whom the QRS complexes in V_{4R}, V_1, and aV_R may be difficult to interpret.

Considerable latitude must be allowed in the criteria for right heart strain in infants. For example, two three month old infants with complete transposition of the great vessels were found to have hypertrophied and dilated right ventricles with normal-sized left ventricles at autopsy. The only evidence of right heart strain in the first case was the "Wilson phenomenon." Leads V_1, V_{4R} and aV_R were not abnormal for this age group. In the second patient a tall R in aV_R was the sole evidence of right ventricular hypertrophy.

The recent classification of right heart strain patterns by Donzelot[3] and his associates into "adaptation," "surcharge" and "barrage" types has been generally useful and valid in older children. Briefly, the "adaptation" type is characterized by a mainly inverted QRS in lead I with a slightly elevated S-T segment. The ST-T configuration in leads II and III is not unusual; S-T may be depressed in these leads, but the T waves are upright. In the chest leads the QRS consists of a tall R wave in V_1 and V_4R. There is a tall R in aV_R. The T waves in V_5 and V_6 are upright.

The "surcharge" or incomplete right bundle branch block type of right

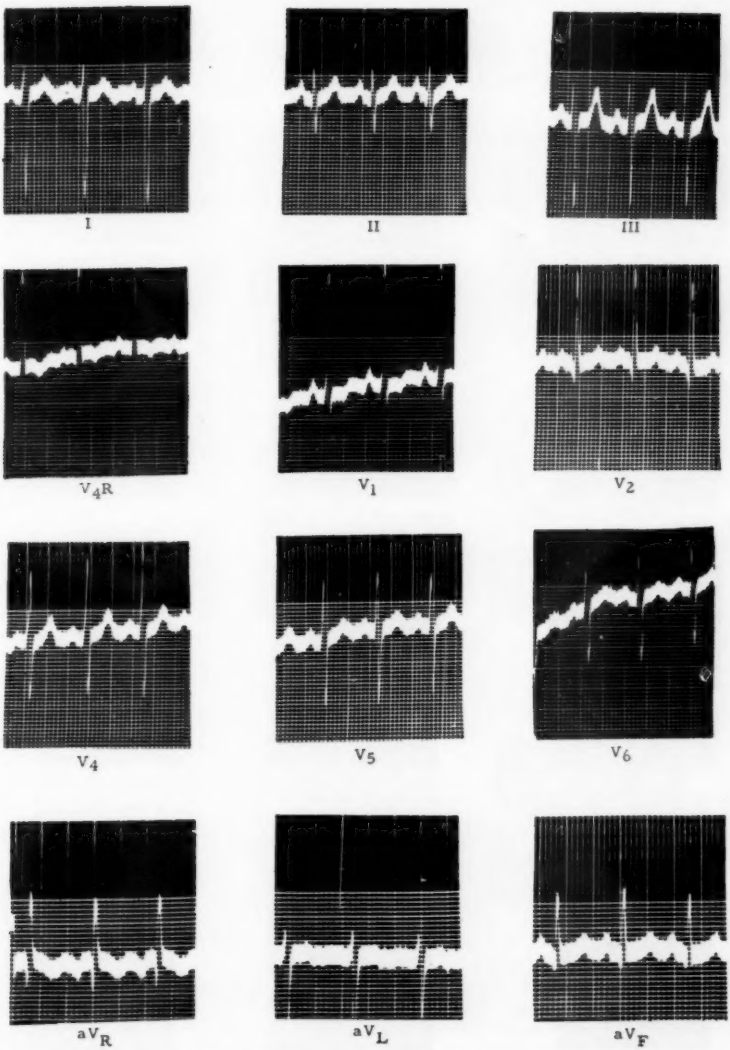

Fig. 20. The "adaptation" or common type of right heart strain. QRS is mainly inverted in lead I; tall and almost completely upright in V_{4R}, V_1 and V_2. Note the progressively smaller R wave and deeper S wave from V_4 through V_6. There is a tall R wave in aV_R.

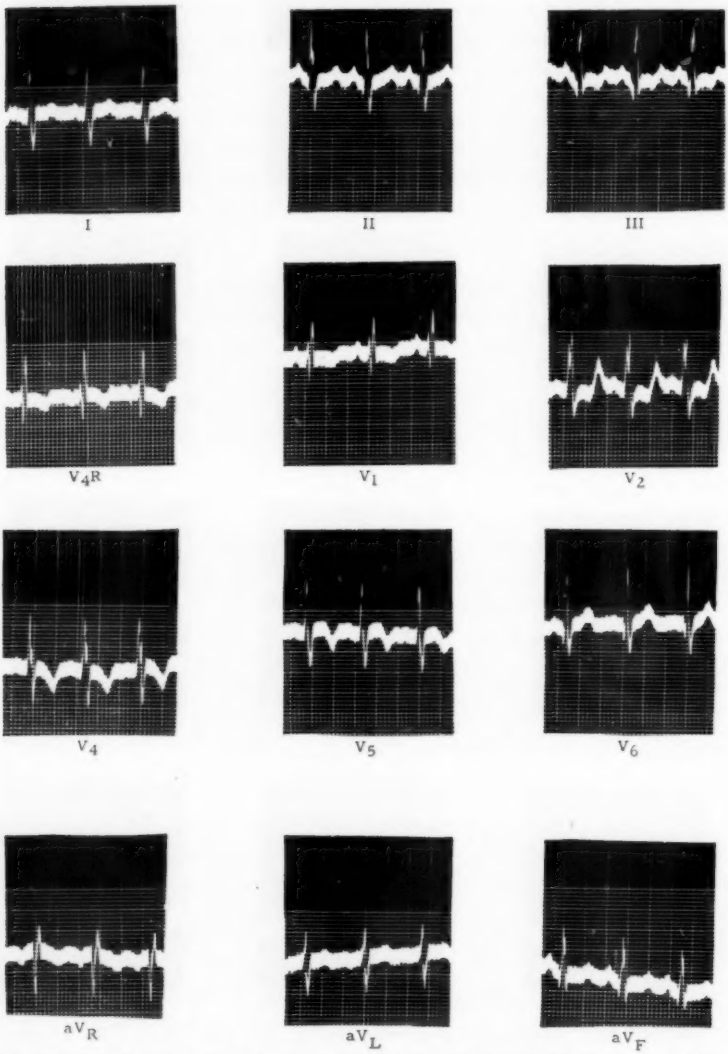

Fig. 21. The "surcharge" or incomplete right bundle branch block type of right heart strain. Note the small R wave and tall R′ in leads V_{4R} and V_1.

heart strain differs from the foregoing in that there is a small R wave followed by a tall R′ in V_1 and V_{4R}

In the "barrage" type the S-T segments in leads II, III, V_1 through V_5 or V_6, and aV_F are all markedly depressed, and the T wave is in-

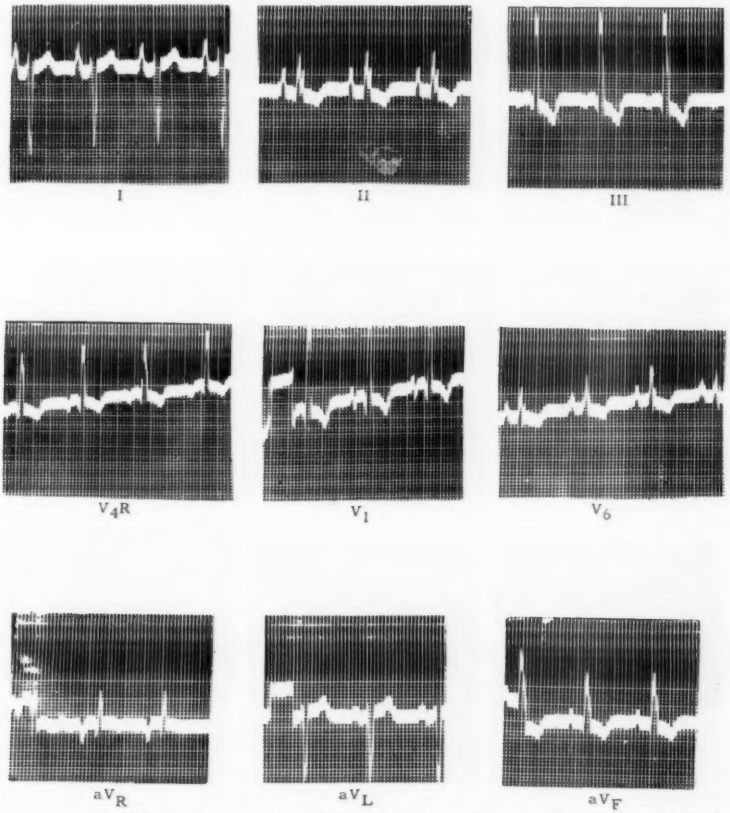

Fig. 22. The "barrage" type of right heart strain. QRS is inverted in lead I, S-T is elevated and the T wave is upright. S-T is depressed and the T wave is inverted in leads II and III. There is a tall, completely upright QRS in V_{4R}, V_1, and all across the chest to V_6. There is a tall R in aV_R. QRS is tall and upright, S-T is depressed and the T wave is inverted in aV_F. Note the peaked, tall P waves in leads I and II.

verted. Usually an inverted QRS with slightly elevated S-T segment and upright T wave is seen in leads I and aV_L.

Although he found some variation, Donzelot generally associated the "adaptation" type with the tetralogy of Fallot, the important factor being the presence of a large interventricular septal defect which allowed an

alternate pathway for blood to escape from the right ventricle, other than through the obstructed pulmonary artery. No such "easement" exists in pulmonary stenosis with an intact ventricular septum. In our series the "adaptation" type is the most common right heart strain pattern, occur-

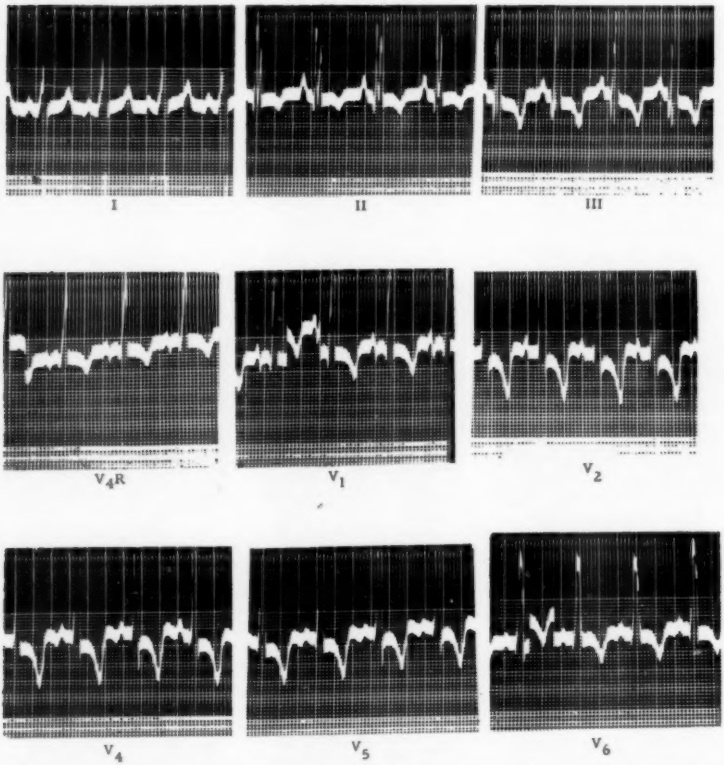

Fig. 23. Preoperative tracing from a child with pulmonary stenosis and an intact ventricular septum. Typical "barrage" type of right heart strain. T waves inverted in leads II and III, the strain pattern of huge R wave, depressed S-T and inverted T wave shown from V_{4R} across to V_6.

ring in every type of congenital heart disease that is accompanied by right ventricular hypertrophy.

The "surcharge" right heart strain pattern was correlated by Donzelot with interauricular septal defects. This incomplete right bundle branch block pattern has been estimated by various writers to occur in 80 to 95 per cent of all proved interauricular defects, and this is generally true in our cases. This pattern is also frequently found in interventricular septal defects.

Regardless of the anatomic diagnosis, however, many children will show incomplete right bundle branch block, then the adaptation type of right heart strain with time, in either interauricular or interventricular septal defects, or the tetralogy of Fallot. In some cases of pulmonary stenosis with an intact ventricular septum, especially those with normal or mod-

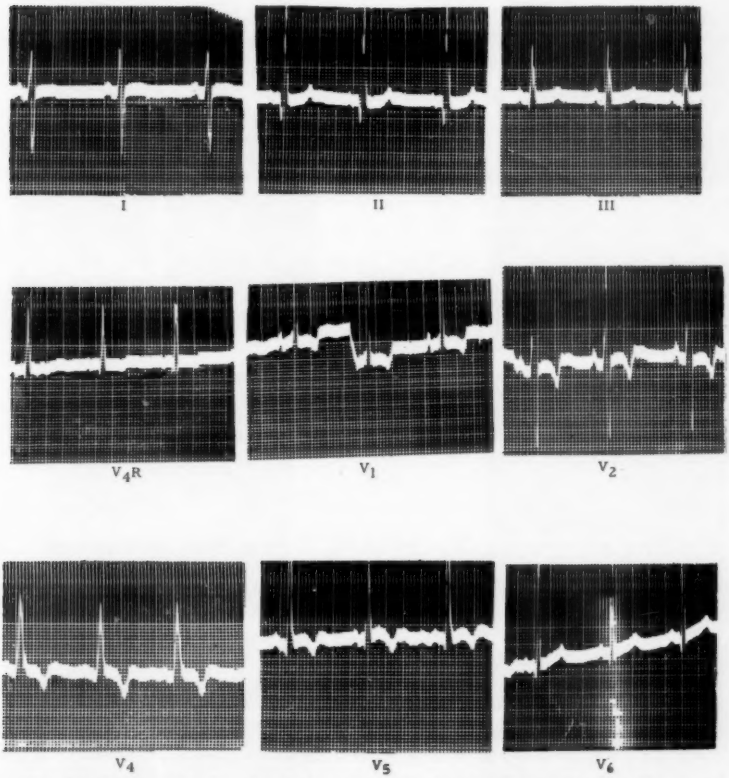

Fig. 24. Postoperative tracing from same patient as in Figure 23. The T wave is upright in leads II and III. The T wave is now upright in V_6. S-T depression has disappeared in the chest leads.

erately enlarged hearts, the electrocardiogram shows either the "surcharge" or "adaptation" patterns, and then progresses to the full-blown "barrage" right heart strain pattern as the heart enlarges.

Consequently we have the clinical impression that these patterns may represent "degrees" of right heart strain. Certainly in the "barrage" type, heart size seems to be one of the controlling factors. As the right ventricle enlarges and presents more and more of its surface to the anterior chest

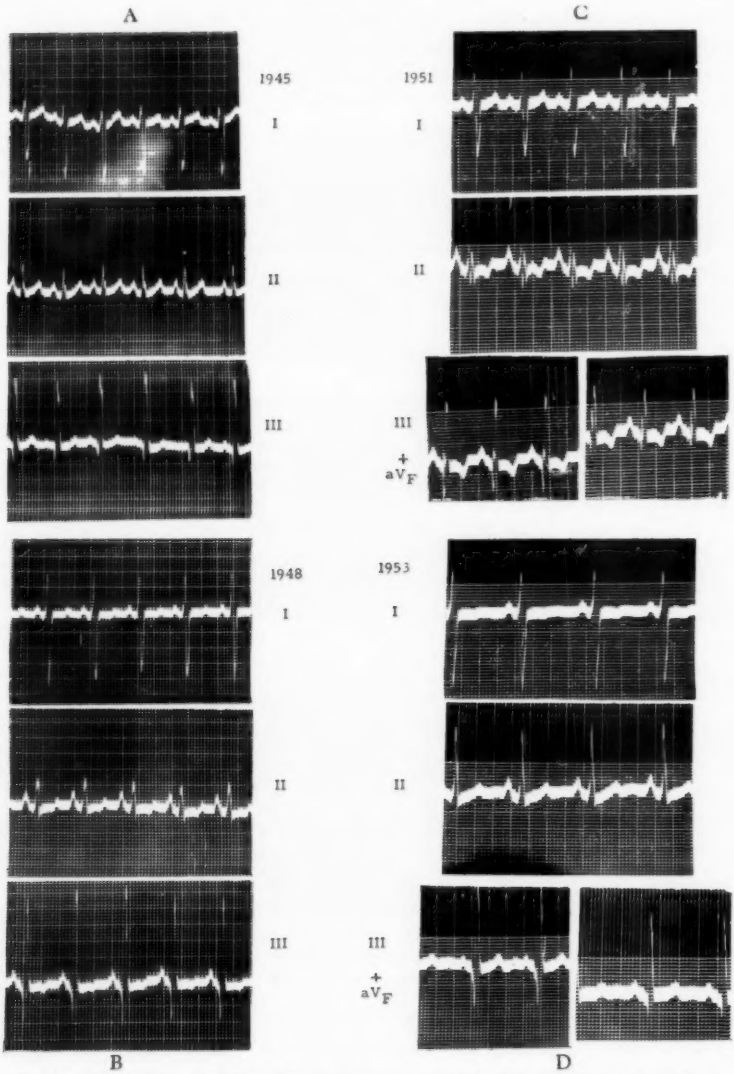

Fig. 25. Evolution of electrocardiogram in patient with pulmonary stenosis with intact ventricular septum. *A* (1945), Note that T waves are upright in leads II and III. *B* (1948), S-T is depressed and the T wave is now diphasic in leads II and III. P wave is taller in lead II. *C* (1951), T waves now sharply inverted in leads II and III. There is a tall R, depressed S-T and inverted T wave in aV$_F$ (and all the chest leads, not shown). *D* (1953), Six months after valvulotomy. The T waves are now upright in leads II, III and aV$_F$.

wall, the tall QRS, depressed S-T and inverted T wave strain pattern appears progressively farther to the left in V_4 than in V_5 and V_6. At the same time the S-T segments in leads II and III become depressed, and the T waves flatten out and finally become inverted. We have the distinct impression that the T waves in leads II and III seem to change with changes in right ventricular pressure, whereas the QRS, S-T segment and T wave changes in the precordial leads are directly related to the heart size.

After relief of the pulmonary stenosis by the Brock valvulotomy the process slowly reverses. The T waves in leads II and III become upright and the typical strain ST-T pattern disappears first in V_6, then in V_5, as the heart size decreases.

LEFT HEART STRAIN

Correlation of electrocardiograms with postmortem findings has shown that left heart strain patterns may vary and evolve with the age of the patient, especially in infants. A ventricular complex in leads V_{4R} and V_1, consisting of a QS, or of a tiny R and a deep S wave, is evidence of left heart strain in infants, and often precedes any changes of diagnostic value in the limb leads or left-sided chest leads. The extremely small amplitude of the T wave normally seen in many infants, and the occasional marked variation in amplitude of both the QRS and T waves with respiration, may limit the amount of information to be obtained from these leads. The T wave in leads V_5 and V_6 normally may be inverted in the first twenty-four to forty-eight hours of life, just as the T wave of the right-sided chest leads are not inverted to form the familiar juvenile pattern until the infant is a few days old. In general, however, the usual patterns for left heart strain, a tall upright QRS with a depressed S-T segment, and small, isoelectric or inverted T waves in leads I, V_5 and V_6, and aV_L in more horizontal positions of the heart, or in leads II, III, V_5 and V_6, and aV_F in the vertical positions, are the commonly occurring and dependable ones in infants and children with congenital heart disease, and correlate well with the postmortem finding of left ventricular dilatation and hypertrophy.

The diagnosis of *idiopathic hypertrophy of the heart* has been replaced by a group of clinical entities whose classification depends, to a significant degree, on the electrocardiogram. The records from patients in this group of diseases may show left heart strain patterns that cannot be differentiated from those seen in coarctation of the aorta or tricuspid atresia. However, a significant percentage of these records may show specific changes that have been well established in adults. These changes may help to separate the "idiopathic hypertrophy" group into myocarditis, anomalous origin of the left coronary artery, glycogen storage disease of the heart, congenital fibroelastosis, and congenital rhabdomyoma of the heart.

In an occasional acyanotic infant with a severely *enlarged heart* the electrocardiogram reveals a general flattening or loss of amplitude of the T

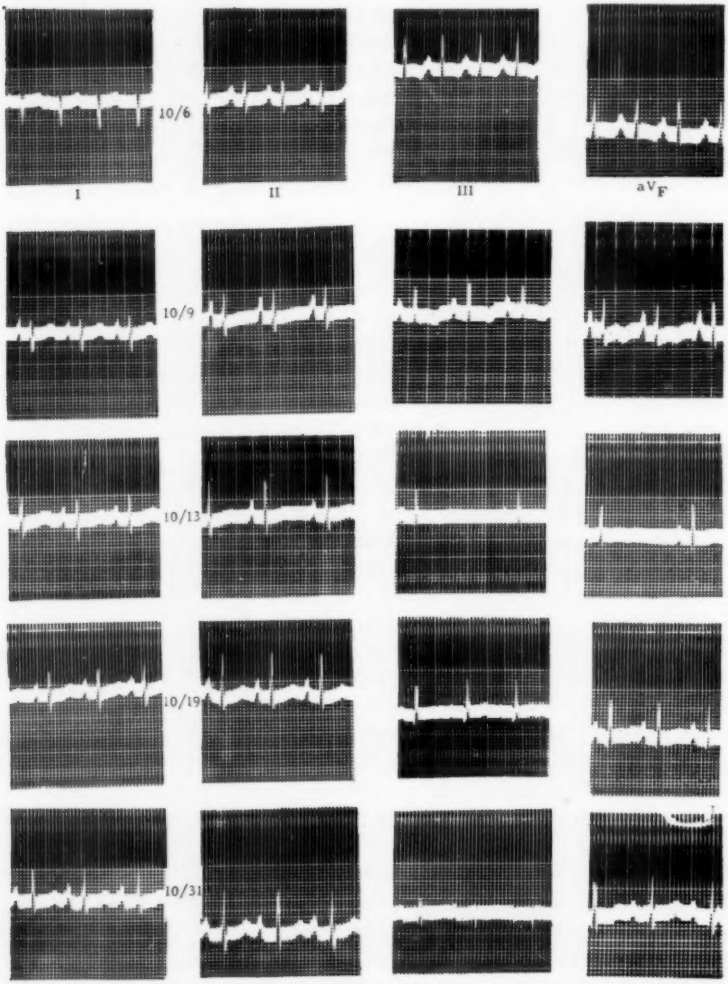

Fig. 26. Diffuse myocarditis. Typical evolution of electrocardiogram over period of one month. Note especially the T wave changes in lead II and in aV_F.

waves in every lead in which the QRS is upright; S-T may be slightly elevated, isoelectric or slightly depressed. The records do not show the typical ST-T changes of left heart strain, and the ST-T configuration may

vary from record to record. Postmortem findings have been those of a diffuse myocarditis. Sufficient cases have been reported in the literature to

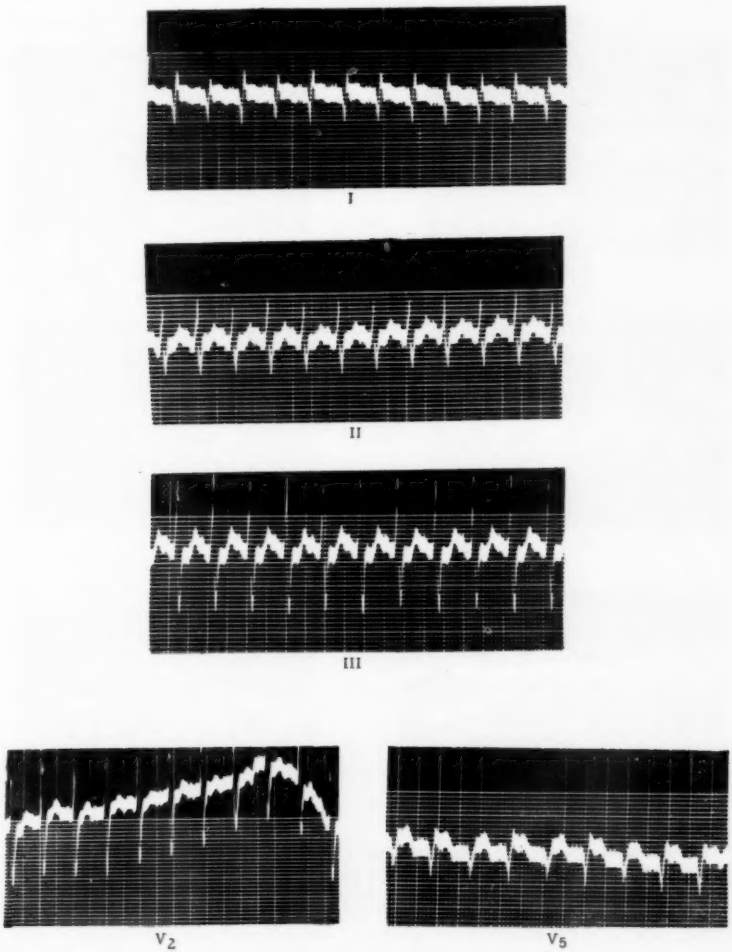

Fig. 27. Anomalous origin of left coronary artery from the pulmonary artery. Aneurysm of left ventricle. There is a deep Q wave in lead I and V_5. S-T elevation and inversion of T wave in lead I. Note the marked S-T elevation in V_5. Age 4 months.

warrant the conclusion that there is a dependable electrocardiographic pattern of myocarditis.

The coronary patterns seen in *anomalous origin of the left coronary*

artery have been adequately described in numerous reports,[9, 10] and are similar to the electrocardiographic patterns of anterior wall myocardial infarcts in adults.

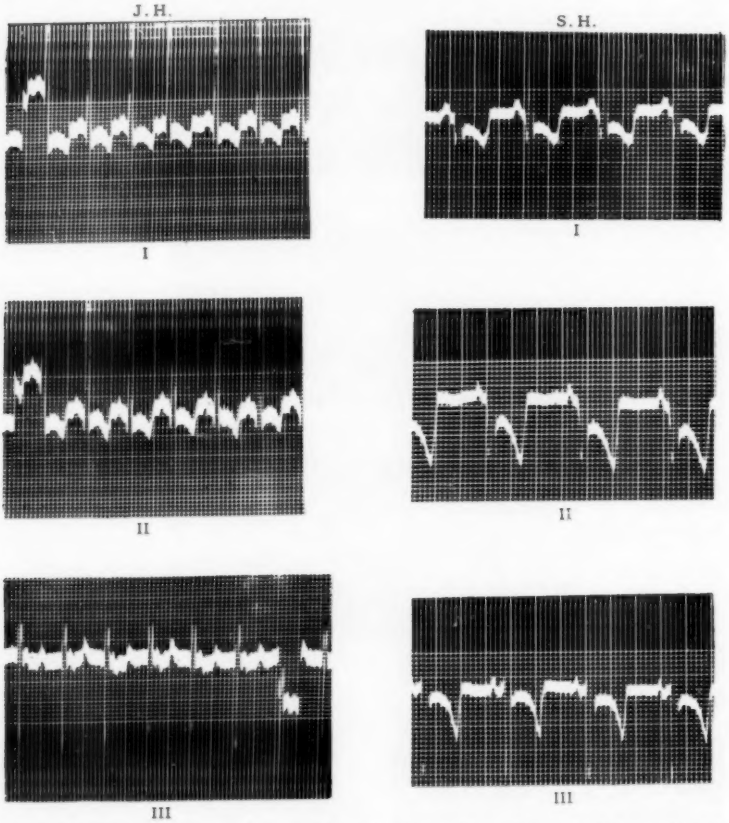

Fig. 28. Glycogen storage disease of heart in sisters. Note the marked depression of the S-T segment and inverted T waves in leads I and II in both cases and in lead III in S.H. Compare with electrocardiogram in cases of di Sant' Agnese or Clement. (See text.)

In one of our cases a full-blown coronary pattern of the elevated S-T type persisted until the infant's death at 4 months. The patient had a mass adjacent to the heart on x-ray examination. An angiocardiogram revealed dye passing into this mass from the left ventricle, and at autopsy a typical aneurysm of the left ventricle was found, as was the anomalous origin of the left coronary artery from the pulmonary artery.

It may be difficult, however, even in retrospect, to distinguish some coronary patterns from left heart strain in the infant group.

Glycogen storage disease of the heart is extremely rare. However, be-

cause it may occur in siblings as reported by di Sant'Agnese[4] and others,[5, 6] it may be important to make a premortem diagnosis. In reviewing the electrocardiograms of our 2 cases (sisters) and comparing them with those illustrated in the literature, a consistent pattern was noted. A left heart strain pattern, characterized by severely depressed S-T segments with sharply inverted T waves in leads I and II, and usually lead III, was found. This exaggerated ST-T strain pattern in the limb leads in infants has been seen only in glycogen storage disease of the heart in our series, and the electrocardiograms shown in the cases of di Sant'Agnese,[4] Clement,[6] Sprague[7] and Mutgeert[8] are almost identical with ours.

In an acyanotic infant with a large heart and no other cardiac or x-ray findings, in whom episodes of paroxysmal tachycardia occur, *congenital rhabdomyoma* of the heart, although rare, should be kept in mind. The usual infant with paroxysmal tachycardia has a normal-sized heart between attacks. Arrhythmias have been noted in every case of congenital rhabdomyoma of the heart reported in the literature[18, 19, 20] when an electrocardiogram was obtained, and was present in our case.

In the remaining acyanotic children with large hearts and no other consistent physical findings, when the electrocardiogram has revealed left heart strain of the common type, with no evidence of the myocarditis, coronary or "glycogen storage disease" patterns, the diagnosis of *congenital fibroelastosis* has been made with good correlation at autopsy.

COMBINED HEART STRAIN

The diagnosis of combined heart strain, in this discussion, is used only when definite patterns of left and right heart strain appear in the same electrocardiogram. In many postmortem cases in which both ventricles are enlarged the electrocardiogram fails to show combined heart strain; but when this pattern does appear in the electrocardiogram, there has been consistently good correlation with the postmortem findings.

P WAVE CONTOUR

Peaked, prominent P waves are a common finding in congenital heart disease, especially in the cyanotic group. However, patterns of P wave contours comparable to the P pulmonale or P mitrale have not been seen. The lesions in which peaked P waves are most commonly seen—pulmonary stenosis with intact ventricular septum, tetralogy of Fallot, tricuspid atresia, complete anomalous venous return, transposition of the great vessels and Eisenmenger's complex—are all in the cyanotic group and thus associated with right-to-left shunt, with the possible exception of "pure" pulmonary stenosis (and it is rare that the foramen ovale is not patent at some time in those cases).

When the P wave is peaked and prominent, it is practically always of greatest amplitude in lead II; it may be seen in leads II and III, I and II, and occasionally in all three limb leads. In the electrocardiograms from 60 postmortem cases of various congenital cardiac defects chosen because of peaked P waves in lead II, it was interesting to note that, with one exception, whenever the P wave in lead III was also prominent, there was a functionally patent foramen ovale or auricular septal defect found at autopsy. However, in a significant number of specimens with the same auricular defects, no P wave abnormalities were present in the electrocardiogram.

Tall peaked P waves, up to 10 mm. in amplitude, are most characteristically found in pulmonary stenosis with an intact ventricular septum, and in our series of 40 patients who underwent valvulotomy, are present in all but 4.

THE ELECTROCARDIOGRAM IN DIFFERENTIAL DIAGNOSIS

Patent Ductus Arteriosus

In the pediatric age group the vast majority of patients coming to operation for patent ductus arteriosus have a normal electrocardiogram or a nonspecifically abnormal one without strain patterns. An occasional case with a large left-to-right shunt may show left heart strain, and a rare case with pulmonary hypertension right or combined heart strain. But the absence of strain patterns has been so consistent in our 260 cases operated upon that the finding of such a pattern raises the suspicion of an additional lesion, or an incorrect diagnosis. Left heart strain was present in only 7 per cent of our cases. However, left heart strain may be evidence of a subaortic stenosis, which becomes evident only after the machinery murmur of the ductus is eliminated by operation. Left heart strain is also present in patent ductus arteriosus with a coarctation of the aorta—not a rare combination. Thus even left heart strain often cannot be attributed to the ductus alone. Rather than attribute a right heart strain pattern to pulmonary hypertension due to the ductus, another lesion, especially a large interventricular septal defect, should be sought for. Right heart strain patterns due to a ductus alone are extremely rare in children. Other causes of continuous murmurs, such as truncus arteriosus communis with dilated bronchial arteries, or a pulmonary arteriovenous fistula, should be ruled out.

The only electrocardiographic abnormalities seen with any significant frequency in patent ductus arteriosus in our cases have been prolonged P-R interval, which occurs in approximately 10 per cent of the cases, and abnormally horizontal electrical positions (for the age).

The diagnosis of patent ductus arteriosus was made clinically, based on

the physical findings, x-ray of the chest and electrocardiogram, in 259 of our 260 cases operated upon. In the other case the diagnosis was made by cardiac catheterization, which revealed a pulmonary hypertension and a bidirectional shunt through the ductus, through which the catheter was passed.

Coarctation of the Aorta

The electrocardiogram in our series of 40 cases operated upon for coarctation of the aorta reveals a left heart strain pattern in one third of the cases, abnormally horizontal positions and other nonspecific abnormalities in another third, and is normal in the remaining cases. Right heart strain or combined heart strain is a serious prognostic sign, usually indicating an inoperable case, that is, a fetal type of coarctation or a generally hypoplastic aorta combined with intracardiac defects. In 15 postmortem cases of fetal coarctation or hypoplasia of the aorta in which electrocardiograms were obtained, right heart strain or combined heart strain, usually with huge, peaked P waves, was found in every case.

On the contrary, infants with the adult type of coarctation usually show no strain pattern even in the presence of considerably high brachial artery pressures, and left heart strain develops with the passage of years. Thus, if a surgical candidate with coarctation of the aorta has any strain pattern at all in the electrocardiogram, it must be a left heart strain or the child almost certainly has an additional lesion. Rarely, an infant with an adult type of coarctation of the aorta has a huge heart and a left heart strain pattern in the first few months of life. We had 2 such cases in our operative group, one a patient who recovered uneventfully, and the other a patient who died a few days postoperatively and was found to have extensive fibroelastosis primarily involving the left ventricle. It is not unusual for a child with a normal electrocardiogram to have a pinpoint coarctation at operation, nor is it uncommon for children with complaints of headaches and pains in the legs with activity to have normal electrocardiograms.

Septal Defects

The diagnosis of an interventricular septal defect is made when a loud, harsh systolic murmur, maximum low on the precordium in the third and fourth or fourth and fifth interspaces, accompanied by a thrill over the same area, is found on physical examination. In the majority of cases the electrocardiogram shows right, left or combined heart strain patterns, and adds little to the diagnosis. In a small percentage of cases, however, the murmur is more "puffy" than harsh, and the electrocardiogram is normal, as is the heart size. These cases, in our series, carry an excellent prognosis

and probably represent the "maladie de Roger," whereas the cases in which the electrocardiogram reveals strain patterns probably represent high interventricular septal defects involving the membranous portion of the septum, and the outlook is less favorable. In 3 cases of the Eisenmenger syndrome studied at autopsy, the electrocardiogram in each case revealed combined heart strain and peaked P waves in lead II.

The Cyanotic Group, with Decreased Pulmonary Vascular Markings

Pulmonary stenosis with an intact ventricular septum (or pure pulmonary stenosis) must be differentiated from tetralogy of Fallot, because the shunt operations done to relieve the latter will sooner or later prove fatal to patients with the former. The electrocardiogram shows right heart strain with peaked P waves in both conditions. However, the tallest, most distorted P waves are more likely to occur with pure pulmonary stenosis. In tetralogy of Fallot unusually tall, peaked P waves have frequently been associated with pulmonary atresia in our series, and these cases bear little resemblance to pulmonary stenosis with an intact ventricular septum.

The type of right heart strain pattern cannot be used as a differential point unless the "barrage" type is found. This pattern has not been seen once in approximately 400 proved cases of tetralogy of Fallot in our series, and has been seen exclusively in pulmonary stenosis with an intact ventricular septum. The differentiation of these two entities generally remains a clinical one based on such things as the normal-sized heart and history of squatting in tetralogy of Fallot, or the poststenotic dilatation of the pulmonary artery and pulsations of the liver, when present, in pulmonary stenosis with an intact ventricular septum.

The differentiation of pulmonary stenosis with an intact septum from Ebstein's disease is usually based on two points—one from the physical examination, the other from the electrocardiogram. Instead of the long, harsh systolic murmur and thrill in the second left interspace found in pulmonary stenosis, a short, soft systolic murmur without a thrill, or a gallop rhythm with no definite murmur, is likely to be present in Ebstein's disease. Since the problem of ruling out Ebstein's disease usually arises only when cardiac enlargement is present, it is important that right heart strain is a constant finding in pulmonary stenosis accompanied by cardiac enlargement, whereas right heart strain patterns have never been reported in Ebstein's disease.

The electrocardiogram from 11 proved cases of Ebstein's disease—9 from cases reported in the literature,[11-17] and 2 in our series—all reveal an interventricular block. When the number of leads taken has been adequate to determine the pattern, this has been a right bundle branch block in every case. Prolonged auriculoventricular conduction time and peaked P waves in the limb leads are also commonly seen in Ebstein's disease.

Except for an occasional infant in whom it is difficult to rule out the normal right ventricular preponderance, the electrocardiogram in tetralogy of Fallot shows right heart strain with monotonous consistency, and is a necessary part of the preoperative diagnosis. The electrocardiogram offers a clear-cut differentiation between tetralogy of Fallot and tricuspid atresia. In 25 cases of tricuspid atresia in our series the left heart strain pattern was present in every electrocardiogram. In addition, tall peaked P waves in lead II or in leads II and III are almost as constant a finding. In our experience the combination of left heart strain and peaked P waves in the electrocardiogram of a patient with normal heart size, especially in the first year of life, is practically diagnostic of tricuspid atresia. In older children with enlarged hearts and increased vascularity this pattern has been seen in an occasional case of Eisenmenger's complex and in one case of the Taussig-Bing type of transposition, but this pattern is certainly not usual in these cases.

The clinical differentiation between tetralogy of Fallot and transposition of the great vessels with pulmonary stenosis or atresia is difficult and occasionally impossible. The angiocardiogram and the catheterization findings are similar, and the electrocardiogram in both conditions may show right heart strain and peaked P waves in the limb leads. In 2 cases of complete transposition of the great vessels with pulmonary stenosis proved at autopsy which were similar to tetralogy of Fallot clinically, the electrocardiogram revealed a combined heart strain and peaked P waves in leads II and III. This experience has strengthened our feeling that the electrocardiogram in a case of tetralogy of Fallot selected for operation should show right heart strain in every instance except in an occasional infant whose electrocardiogram may reveal no definite strain pattern. Any evidence of left or combined heart strain on the electrocardiogram rules out an uncomplicated tetralogy of Fallot. The combination of tetralogy of Fallot with a large interauricular septal defect is unusual, but when it occurs, it may mimic the clinical, radiologic and catheterization findings of tricuspid atresia, especially in older children, in whom tricuspid atresia is seldom seen. The electrocardiographic pattern of left heart strain and peaked P waves has been a dependable differential point in identifying tricuspid atresia in these older patients.

The types of cyanotic congenital heart disease discussed up to this point have been in the group with decreased vascularity of the lung fields on x-ray examination. The cyanotic group with increased vascularity of the lung fields includes (*a*) complete transposition of the great vessels, (*b*) complete anomalous drainage of the pulmonary veins into the right auricle (usually via the coronary sinus, innominate or portal veins), (*c*) the Eisenmenger complex, and (*d*) the Taussig-Bing type of transposition (aorta originating from the right ventricle, pulmonary artery overriding a high interventricular septal defect). The diagnosis in this group of dis-

eases is usually not difficult from the history, physical examination and roentgenogram of the chest. We have found no dependable way to differentiate these conditions from their electrocardiographic patterns. However, in 20 proved cases of complete transposition, right heart strain with peaked P waves was found in all but 4 cases, 2 of which showed combined heart strain, and in 8 proved cases of complete anomalous venous return in our series, right heart strain with peaked P waves was found in every instance. Conversely, combined heart strain is found in a large percentage of cases of the Eisenmenger and Taussig-Bing complexes.

In general, the electrocardiogram in these cases shows right heart strain until the heart becomes considerably enlarged. The appearance of the combined heart strain pattern has been a serious prognostic sign in this group.

ANOMALIES OF THE HEART'S POSITION

A detailed discussion of anomalies of position of the heart and its chambers is beyond the scope of the present article. This group includes the cases of situs inversus with mirror image dextrocardia, simple dextroposition (both of which are likely to occur with otherwise normal hearts) and the partial heterotaxias—isolated dextrocardia and isolated levocardia—in which an operable type of cyanotic congenital heart disease is frequent.

If the P wave originates from the sino-auricular node, its direction in lead I provides important information about the anatomic position of the auricles. For example, in isolated levocardia the P wave in lead I is often inverted, the auricles being in the reversed position, while the ventricles remain normally situated. Infundibular pulmonic stenosis, large interauricular and interventricular defects, partial transpositions of the great vessels, and anomalies of the vena cava complete the picture usually found in isolated levocardia. The result is a heart physiologically similar to a tetralogy of Fallot. The electrocardiogram shows right heart strain, and prominent P waves in lead II, and the patient is often relieved by a systemic-pulmonary shunt operation.

In isolated dextrocardia the P wave in lead I may be inverted (as in the usual mirror image dextrocardia found with complete situs inversus), or it may be upright, showing the auricles and the sinus node to be in their usual relationship. The ventricles may or may not be in the mirror image position, in which instance lead I is a mirror image and leads II and III are reversed. If sufficient precordial leads are obtained, from V_{6R} to V_6, and if aV_L is read as aV_R, what would be a right heart strain pattern in a normally placed heart is usually found. As in isolated levocardia, an infundibular type of pulmonary stenosis is usually found in isolated dextrocardia, and many of these patients are improved by a shunt operation of the Blalock or Potts type. In 25 of 27 cases of isolated dextrocardia in our

series, a cyanotic type of congenital heart disease was present. All 12 cases of isolated levocardia in our group were cyanotic types.

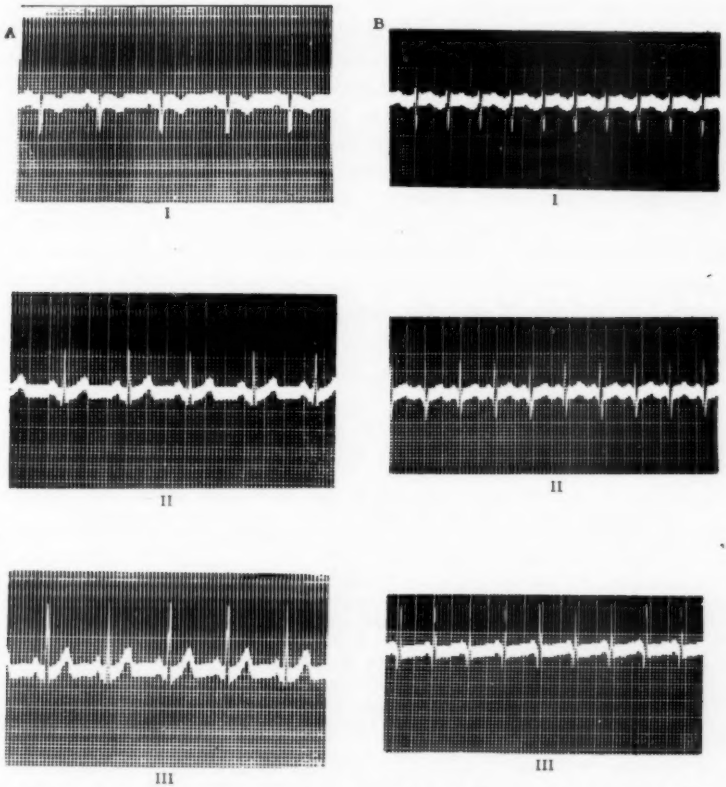

Fig. 29. A, Isolated dextrocardia. The P wave is upright in lead I and the QRS-T pattern of the limb leads is that of mirror-image dextrocardia. *B*, Isolated levocardia. The P wave is inverted in lead I, but the QRS-T pattern shows the ventricles to be in the normal position. The inverted QRS and slightly elevated S-T segment in lead I is due to a superimposed right heart strain pattern in this case.

SUMMARY

The electrocardiographic findings in infants and children with congenital malformations of the heart have been presented from the clinical standpoint. In the acyanotic patients the electrocardiogram has been discussed in three groups: (1) patent ductus arteriosus and coarctation of the aorta, (2) the septal defects, (3) the "idiopathic hypertrophy" group. In this group various recurring electrocardiographic patterns have been

shown to aid in separating these cases into at least five types, each with a characteristic electrocardiogram.

The cyanotic patients have been discussed in four groups: (1) with a relatively normal-sized heart and decreased pulmonary vascular markings. This group includes tetralogy of Fallot, transposition of the great vessels with pulmonary stenosis or atresia and tricuspid atresia. (2) With enlarged hearts and decreased pulmonary vascular markings. This group includes pulmonary stenosis with an intact ventricular septum and Ebstein's malformation. (3) With increased pulmonary vascular markings. This group includes complete transposition of the great vessels, anomalous pulmonary venous return, Eisenmenger's complex and the Taussig-Bing heart. (4) The final group of patients discussed includes the anomalies of the heart's position, particularly isolated levocardia and isolated dextrocardia, in which the electrocardiographic pattern of pulmonic ventricular strain is superimposed upon the changes characteristic of anomalous relationships of the heart's chambers.

The section on Idiopathic Cardiac Hypertrophy was written in collaboration with Dr. Frank N. Johnson.

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ANGIOCARDIOGRAPHY IN INFANTS AND CHILDREN

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In recent years angiocardiography has been widely used in the investigation of congenital heart disease. Many papers on the subject have been published since 1937, when Castellanas[2] and his co-workers first visualized the right side of the heart. It has proved a useful technique to display in a vivid form the pathology of many types of congenital heart anomalies. It is the purpose of this paper to indicate the defects that may be elucidated by this procedure and to discuss the place it holds in our diagnostic armamentarium.

Numerous types of apparatus have been devised to carry out angiocardiography. Neuhauser[17] at Boston Children's Hospital pioneered in this field with a simply designed but useful apparatus in 1943. A very practical unit has been described by Scott[22] and is available commercially. This machine takes radiographs at two per second. In the past few years several Swedish investigators have devoted a good deal of time to this problem and developed excellent angiocardiographic equipment. Several machines have become available that take radiographs in two planes. These have distinct advantages over those of the one-plane variety. The number of radiographs taken per second is important, since, as Wegelius and Lind[24] point out, a baby's heart may be beating at 180 per minute, or three per second. At this rate systole is about twice diastole; therefore nine radiographs per second will be required to demonstrate both systole and diastole in each heart cycle. The author is currently using an apparatus designed by Lind[14] which will, at full speed, take ten radiographs per second in two directions.

Kjellberg has recently described a technique for angiocardiography using an intracardiac catheter, forced injection and an x-ray exposure time of 1/250 second. With this method a concentration of contrast medium

Aided by a grant from the Ontario Heart Foundation, Canada.

can be obtained at the point of interest, and the short exposure eliminates minor degrees of blurring from movement. This is most important in babies whose hearts may be beating at 150 to 200 per minute.

Two methods of study have proved useful in outlining various congenital heart anomalies: (*a*) the venous angiogram, which allows one to visualize the right side of the heart, pulmonary artery and shunts from right to left; (*b*) the aortogram, which visualizes the aortic arch and descending aorta, thus demonstrating such defects as patent ductus arteriosus or coarctation of the aorta. One or two other less known anomalies may also be visualized by this method.

VENOUS ANGIOGRAM: TECHNIQUE

The baby is given a sedative, usually ¾ grain of Seconal by rectum, one-half hour before the procedure. The femoral vein is exposed, and

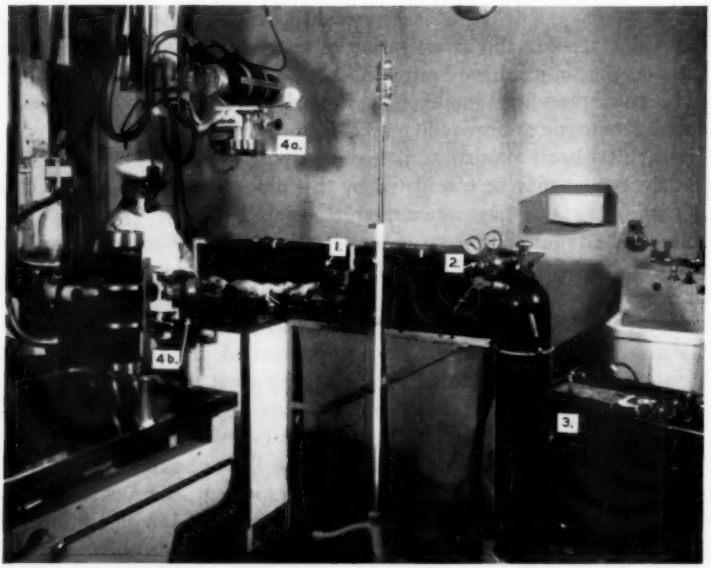

Fig. 30. Showing an infant on the angiocardiography machine with needle, tubing (*1*), compressed air (2) and electrocardiograph (3) in place. X-ray tubes (*4*) take radiographs in two directions at 10 per second; the contrast medium is automatically released and injected at a prearranged interval after the x-ray machine has started.

through a short incision a no. 16 needle is inserted with a continuous intravenous attached. The intravenous fluid is run in from the side with a stopcock which can be turned to permit the injection of the contrast medium. When a venous angiogram is to be done, 70 per cent diodrast is

used. In the aortogram 35 per cent is used, since 70 per cent in full concentration may affect the vasomotor or respiratory centers. The diodrast is held in a syringe encased in a cylinder that is activated by compressed air.* Figure 30 shows the needle, tubing, compressor and compressed air. The x-ray machine is equipped with a timer and delaying unit so that the injection can be started at a selected interval. The amount of 70 per cent diodrast injected varies with the weight of the child. For newborn babies usually 8 to 10 cc. are adequate; at six months to a year, 12 to 13 cc. may be required; at two years of age 15 cc. are usually sufficient. In the five to ten year age group, 20 to 30 cc. are needed. Regardless of age, a large heart usually requires more contrast medium than a small heart for adequate visualization. Radiographs are taken simultaneously in two directions.

If an intracardiac injection is planned, a catheter is inserted into the femoral vein and guided to a suitable position in the right ventricle or other chambers. The procedure is then carried on as before.

AORTOGRAM: TECHNIQUE

The skin of the arm is incised at the point of junction of the ulnar and radial arteries where they join to form the brachial. In infants the brachial artery is used for the injection, and in older children the radial artery is used. A no. 18 or 16 needle with stilet is inserted, and the needle is tied in with a ligature around the artery. At the proper moment an injection of 35 per cent diodrast is made and a series of radiographs taken in two directions to follow its course. Most of our studies with this particular procedure have been limited to the first two years of life. In older children it is difficult to overcome the blood pressure by this countercurrent method. Although we have not encountered any deleterious effects in the older children, it would seem likely that there is more risk than in babies because of the greater pressure necessary, and also because one usually has to tie off the vessels used.

RISKS OF ANGIOCARDIOGRAPHY

In considering angiocardiography as a diagnostic procedure the first thing one must face is the fact that there is some degree of risk in its use. This should of course be more than balanced by the possible gain in information. Several studies have been reported on the risks involved. In 1942 Pendergrass[18] and his colleagues found that in 661,800 patients who had diodrast injections intravenously, twenty-six deaths occurred. These injections were chiefly for urography and were given rather slowly. More recently Dotter and Jackson[4] have surveyed hospitals doing angiocardiog-

* This apparatus was designed by the author and Mr. E. A. Foster, Hospital for Sick Children, and is now available commercially from J. F. Hartz and Co., Toronto, Canada.

raphy and have collected records of 6824 such examinations with twenty-six deaths, a mortality of 0.38 per cent. In 23 cases occurring in North America, 21 had congenital heart disease. Seventeen were cyanotic, and 4 noncyanotic. Most of the deaths were in children under the age of eight, and most were cyanotic. These deaths were chiefly among children who had received relatively large doses of contrast medium. Furthermore, over half of the deaths were associated with multiple injections of diodrast. In 19 of the reported fatalities following angiocardiography, sensitivity testing was done and in each case was negative. Therefore sensitivity tests do not aid in determining susceptibility of the patient beforehand. Morgan[16] reports 2 fatal cases each given 1 cc. of diodrast only. In both, death followed immediately after this small dose. From his survey Dotter concludes that two types of catastrophe may occur: one from respiratory arrest, and one from circulatory collapse.

The immediate reaction, probably due to respiratory arrest, is exemplified by our only fatality, which occurred in a child three years of age who was very cyanotic before the investigation, and died ten to fifteen minutes after the angiogram was carried out. At postmortem examination she was found to have tetralogy of Fallot with pulmonary atresia. The second type of reaction, due to circulatory collapse, may come after one injection, but is more liable to occur after multiple injections of contrast medium. One of our patients had a delayed reaction after receiving two diodrast injections one-half hour apart. The patient had returned to the ward and about one-half to one hour after his second injection he suddenly collapsed, had a weak pulse and marked cyanosis, and it looked for a moment as if he would not recover. He revived quickly with oxygen, however, and soon appeared his usual self.

It appears, then, that the chance of fatal reaction in a child who is not cyanotic is small, probably not greater than one in 1500. A fatal reaction in a cyanotic child is somewhat more likely to occur, possibly one in 300. For this reason each case should be considered separately as to whether the procedure is warranted or not. One should have a thorough investigation of the patient by other means before angiocardiography is considered; then, if it becomes obvious that some specific point in diagnosis or therapy would be helped by this procedure, one is usually justified in proceeding. Since half the deaths occurred after multiple injections, it would seem unwarranted to do more than one injection the same day in a cyanotic child. This re-emphasizes the importance of having an apparatus that will take radiographs in two directions, so that a complete study is made with one procedure.

If an intracardiac injection is planned, the risk is slightly greater than by the ordinary venous or arterial method. The possible gain from this technique should be carefully considered before proceeding.

INVESTIGATION PRIOR TO ANGIOCARDIOGRAPHY

After the usual careful history, physical examination, electrocardiogram, fluoroscopic and special tests such as circulation time, oximetry, dye curves with oximetry, one is usually able to arrive at a fairly accurate diagnosis. A number of cases, however, will require further investigation by catheterization or angiocardiography. When a problem in diagnosis arises at this stage in the investigation, it is necessary to compare one procedure with the other.

Catheterization of the heart will reveal the pressures in the heart in the right auricle, right ventricle and pulmonary artery. Left-to-right shunts may be demonstrated by a rise in oxygen in the right auricle, right ventricle or pulmonary artery. Right-to-left shunts may be demonstrated by the use of Evans blue dye curves, intracardiac ether or fluorescein injections. At times, with catheterization, one may be able to demonstrate the defect by means of direct passage of the catheter through a patent ductus into the aorta from the right ventricle or through an auricular septal defect out into the pulmonary veins. Thus catheterization of the heart will reveal shunts, whether they be right to left or left to right, as well as give valuable information regarding pressures in various chambers and vessels.

Angiocardiography will frequently reveal right-to-left shunts by the passage of dye from right auricle into left auricle or from the right ventricle into aorta. Left-to-right shunts, however, are not delineated by venous angiograms as a rule, and angiocardiography has, therefore, a much more limited scope than catheterization. There are three situations in which the use of angiocardiography is perhaps especially helpful: (1) the countercurrent demonstration by aortogram of coarctation of the aorta or patent ductus arteriosus, or aortico-pulmonary septal defect. Such defects may be determined satisfactorily by other clinical means in most instances, but in some infants and young babies the murmurs and clinical signs are not clear. The aortogram may be of distinct value, especially since the conditions delineated by this method are usually operable. (2) Angiocardiography is useful in the young infants with cyanosis whose heart shapes and electrocardiograms do not fit into any of the readily recognizable patterns. In the newborn period complete cardiac catheterization may be difficult. (3) The angiogram may reveal the site, degree and type of stenosis in tetralogy of Fallot and aid in separating the valvular from the infundibular type of stenosis. The degree of overriding may also be studied.

At the Hospital for Sick Children, Toronto, during the past year, 29 per cent of patients admitted for heart studies had catheterization of the heart, and 15 per cent, angiocardiography. Thus we have favored the former procedure in our congenital heart investigations. As a general rule,

we have found catheterization more helpful than angiocardiography in the older children. In infants in selected cases we have derived much useful information from angiograms.

Catheterization results not infrequently disclose only part of the picture, and may be confusing or misleading at times. The same may be said for angiocardiography, although more frequently the latter procedure simply demonstrates the defect already known to be present and does not clearly delineate the unknown anomalies. In any case, it is necessary, finally, to assemble all the information obtainable by a variety of methods and put this together as one would a jigsaw puzzle.

VENOUS ANGIOCARDIOGRAPHY

Tetralogy of Fallot

In considering the anomalies visualized by angiocardiography, those with cyanosis are almost invariably best studied by the venous angiogram.

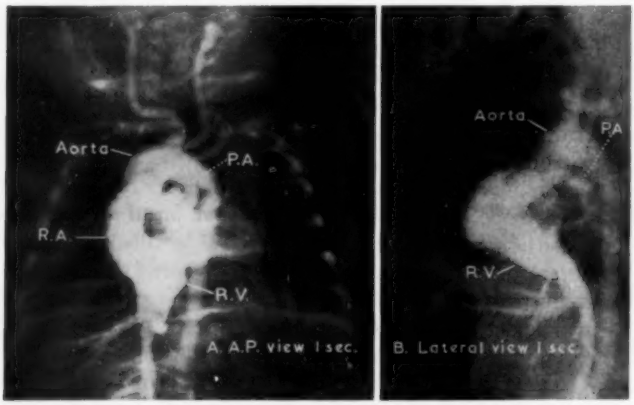

Fig. 31. Tetralogy of Fallot: M. P., age 2 weeks. The simultaneous filling of the right ventricle and aorta is shown in both the anteroposterior and lateral views. In the lateral view the hypoplasia of the pulmonary artery is apparent, as are the fine branches of the pulmonary vessels. Confirmed at autopsy.

Tetralogy of Fallot is the most commonly encountered in this group, but in most instances the diagnosis is clear from the other clinical findings. Occasionally a bizarre cardiac shape occurs in this group, or there is some doubt about the diagnosis in early life; then the angiogram may be useful. An example is shown in Figure 31. The overriding aorta and pulmonary hypoplasia are clearly shown.

In an effort to summarize the information that may be available by

this procedure in tetralogy of Fallot, the following points are listed: (1) simultaneous filling of the aorta and pulmonary artery. (2) The pulmonary artery (*a*) may be smaller than the aorta (this is most commonly the case); (*b*) may show no filling whatever, indicating pulmonary atresia; (*c*) may be equal in size to the aorta in spite of the diminished pressure. (3) The degree of overriding of the aorta may be estimated by (*a*) the position of the aorta in relation to the right ventricle in the lateral view; (*b*) a dense shadow of the aorta in the early angiogram films suggests a greater degree of overriding of the aorta; (*c*) occasionally the aorta may be slightly overriding the right ventricle, and yet may show no filling with contrast medium at all. (4) Size and position of the pulmonary artery and the branches may be demonstrated. This is of considerable importance when the pulmonary artery is only supplying one lung. When the conventional roentgenogram of the heart and chest shows suggestive evidence of a small or absent pulmonary artery on one side only, angiocardiography may be required to confirm this in order to aid the surgeon in deciding which side of the chest to open. (5) Information about the site and degree of the stenosis, whether at the pulmonary valve or the infundibulum, may occasionally be obtained. The size of the infundibular chamber may sometimes be estimated. Usually this area lies so close to other portions of the heart containing contrast medium, such as the aorta and the right ventricle, that it may be difficult to visualize with clarity. The intracardiac technique of Kjellberg with forced pressure may outline the size of the stenotic opening and demonstrate the jet stream into the pulmonary artery. (6) The angiogram may be of some value in differentiating among tetralogy of Fallot, single ventricle with pulmonary stenosis, transposition of the great vessels with pulmonary stenosis, persistent truncus arteriosus, pulmonary valvular stenosis with patent foramen ovale in the anteroposterior view of the angiogram.

Perhaps the chief point of interest in angiocardiography in tetralogy of Fallot at present is the effort to determine the presence or absence of infundibular stenosis, the size and shape of the infundibular chamber, if such exists, or the presence or absence of valvular stenosis at the entrance of the pulmonary artery. This area may be difficult to visualize by routine venous angiogram, probably because there is some overlapping of shadows and because the area concerned is a small one and the flow of contrast medium may be too small or thin for adequate clarity. Goodwin et al.,[9] in reviewing their angiocardiograms, found that they had failed to visualize the site and type of the stenosis in 80 per cent of their cases. Gasul[7, 8] reports that, although they have been able to visualize infundibular stenosis in several cases of tetralogy of Fallot, they have found it an inconstant sign to depend on for diagnosis. Kjellberg, however, by intracardiac injection, has demonstrated the size and position of the infundibular cham-

ber, and can assess the degree of stenosis above or below it. Furthermore, his technique demonstrates the flow from the right ventricle into the aorta and permits an evaluation of the degree of overriding.

In considering the differential diagnosis of tetralogy of Fallot by angiocardiography, several other conditions may show similar shadows. However, certain points usually make differentiation possible. In transposition of the great vessels the aorta in the lateral view can usually be seen arising anteriorly and clearly off the right ventricle. Furthermore, there is frequently a faintly filled but good-sized pulmonary artery visible behind it. In certain cases of persistent truncus arteriosus a clearly cut common trunk can be seen giving rise to an aorta and then the pulmonary arteries. An example of such a case is shown in Figure 38. A single ventricle with a pulmonary stenosis may usually be recognized if two views are taken. The ventricular portion of the heart is completely outlined immediately, and the aorta may come off in a variety of unusual positions.

Pulmonary Valvular Stenosis with Patent Foramen Ovale

An example of this anomaly is shown in Figure 32. One usually sees a somewhat enlarged right auricle, an enlarged right ventricle, a full and

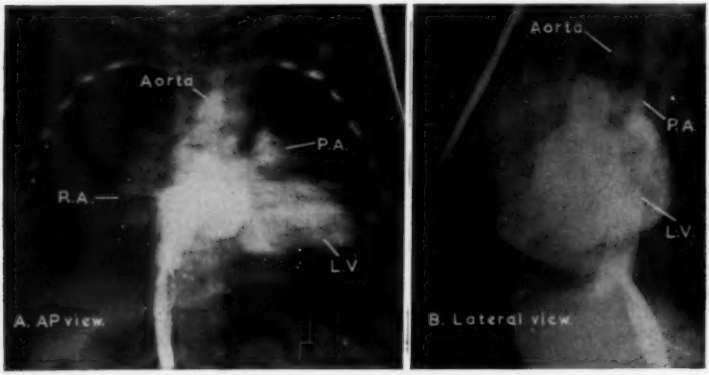

Fig. 32. Pulmonary valvular stenosis with patent foramen ovale: C. M., age 9 months. In the anteroposterior view (a large right ventricle can be seen filling) the pulmonary artery and the aorta can be seen filling together; in the lateral view it is evident that the left ventricle has filled promptly, indicating that the contrast medium has passed from right auricle to left auricle and down into the left ventricle; a dilated pulmonary artery is evident in the anteroposterior view. Confirmed at autopsy.

often dilated pulmonary artery and an aorta that fills at approximately the same time as the pulmonary artery. In the anteroposterior view it may be difficult to tell whether this is tetralogy of Fallot or pulmonary stenosis with patent foramen ovale.

In the lateral view the contrast medium can be clearly seen passing

over from the right auricle into the left auricle, into the left ventricle, and thence out into the aorta. Thus the angiogram may be diagnostic without visualizing the precise site of the stenosis. With intracardiac catheter, Kjellberg has shown the valvular stenosis and demonstrated the jet stream and its flow impinging on the wall of the pulmonary artery.

It has been a matter of some physiologic interest in doing angiocardiography to note that the aorta and the pulmonary artery fill at approximately the same time, indicating that the blood flow through the foramen ovale into the left ventricle and thus into the aorta takes place in approximately the same time as the passage of blood into the right ventricle and into the pulmonary artery.

Transposition of the Great Vessels

Transposition of the great vessels is the second most common cause of cyanotic congenital heart disease, and should be looked for in early life, since these infants usually do not survive more than a few months.

Fig. 33. Transposition of the great vessels: G. M., age 1 year. *A*, In the anteroposterior view the aorta can be seen filling from the right ventricle. *B*, In the lateral view the aorta clearly comes off the large right ventricle; a shadowy outline of the pulmonary artery is also evident; the pulmonary artery is of good size. Confirmed at autopsy.

An angiogram of transposition of the great vessels is shown in Figure 33. One can easily recognize the aorta filling from the right ventricle. This, however, shows with greatest clarity in the left anterior oblique or lateral view. In the anteroposterior view it is frequently difficult to identify its origin. In the lateral view the aorta can be seen coming off the right

ventricle that leaves little doubt regarding its origin. The pulmonary artery fills approximately one second later and is revealed only faintly. When it can be outlined even faintly, it frequently appears larger than the aorta. The pulmonary branches are then somewhat larger than seen in tetralogy of Fallot and fill less distinctly.

Ventricular septal defects are usually not shown. Auricular septal openings may be shown by continuous or intermittent filling of the left auricle from the right auricle. When the flow is large and continuous, it is either an auricular septal defect or an abnormally patent foramen ovale. When the flow is slight and intermittent, it is usually a normal foramen ovale opened by the sudden rise in right auricular pressure.

The right auricle may be normal or slightly enlarged. The right ventricle is often enlarged.

Taussig Heart

An example of this anomaly is shown in Figure 34. It reveals an aortic shadow similar to that in transposition of the great vessels with the aorta

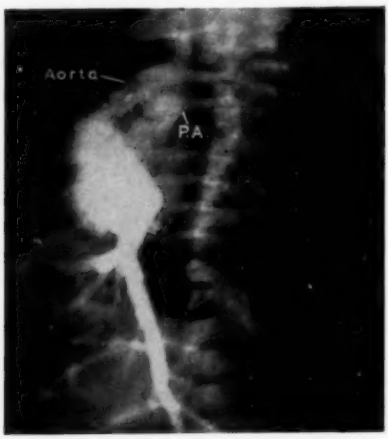

Fig. 34. Taussig heart: A. D. L., age 3 months. The aorta arises clearly from the right ventricle. The pulmonary artery also accepts contrast medium from the right ventricle. At the same time one can see the stream of blood from the left ventricle containing no contrast medium joining that from the right ventricle as it flows into the pulmonary artery.

coming clearly off the right ventricle. Since the pulmonary artery overrides both ventricles, it fills with contrast medium well, and is outlined immediately more clearly and more rapidly than one sees in straightforward transposition of the great vessels. At the same time one can see the stream of blood from the left ventricle, which contains no contrast

medium, joining that from the right ventricle as it flows into the pulmonary artery.

Tricuspid Atresia

Tricuspid atresia is a condition that usually can be diagnosed by the electrocardiogram, and this obviates the necessity of angiocardiography in most cases. In early infancy, however, it occasionally may be difficult to differentiate between tricuspid atresia and certain cases of single ventricle with left axis deviation in the electrocardiogram. The angiocardiogram may then be of limited value. A typical example is shown in Figure 35.

Fig. 35. Tricuspid atresia and patent ductus: F. H., age 3 weeks. The contrast medium streams rapidly into the left ventricle, which shows a denser shadow than the rest of the heart. The aorta and the hypoplastic pulmonary artery can be seen filling together. Confirmed at autopsy.

Tricuspid atresia shows a typical pattern with the contrast medium flowing from right auricle to left auricle into left ventricle and filling the aorta promptly. The pulmonary artery fills in reverse direction from the left ventricle into the vestigial right ventricle and thus into the pulmonary artery. The right auricle may be of good size, but may not show up clearly in the first few radiographs, since the contrast medium goes through a central channel without adequately filling the peripheral portions of the auricle.

The left ventricle appears quite different in shape and size from the right ventricle, and usually shows up as a round ball in the left anterior oblique and lateral views. The pulmonary artery, as one might expect, is usually small with fine, lacy vascular branches out into the lung field. Occasionally a patent ductus may show up in the venous angiogram, since the concentration of contrast medium in the aorta is greater than usual. Figure 36, A, shows clearly the direction of the blood flow through a

foramen ovale and down into the left ventricle, and thence out into the aorta and a hypoplastic pulmonary artery.

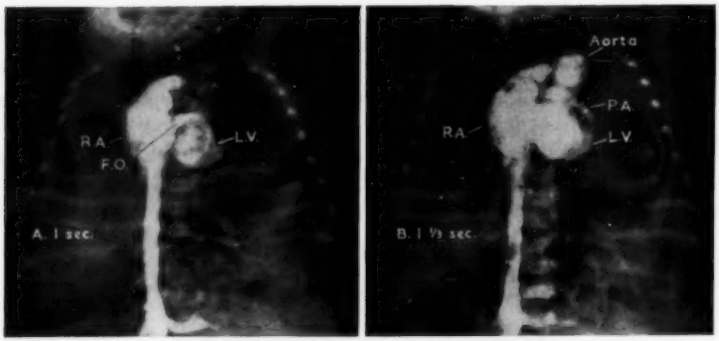

Fig. 36. Tricuspid atresia or stenosis: C. G., age 5 weeks. A, The contrast medium can be seen filling the right auricle and passing across through a patent foramen ovale and down into the left ventricle. B, The aorta can be seen filling from the right ventricle. At the same time the hyoplastic pulmonary artery is filling part way out into the lung field. This patient has had successful operation.

Single Ventricle

The diagnosis of single ventricle is often a problem, since these cases may have right or left ventricular hypertrophy. They may simulate te-

Fig. 37. Single ventricle and pulmonary stenosis: J. A., age 3 years. This figure shows a large single ventricle which has filled promptly and totally from the right auricle. Confirmed at autopsy.

tralogy of Fallot, tricuspid atresia, persistent truncus arteriosus, especially if the single ventricle is associated with pulmonary stenosis.

An angiogram of a single ventricle is shown in Figure 37. It reveals a

large single ventricle which has filled promptly and totally with contrast medium. A large aortic shadow is shown coming off in an unusual position. In single ventricle the aorta may arise in a variety of places in relation to the cardiac outline.

The small pulmonary artery shadow is shown, indicating pulmonary stenosis. (These findings were confirmed at autopsy.)

Persistent Truncus Arteriosus

An example of truncus arteriosus is shown in Figure 38. One can visualize a moderate-sized right auricle and right ventricle with a large single trunk, dense with contrast medium, arising out of the center of the heart. The aorta is continuous with this central trunk, and arising from it are

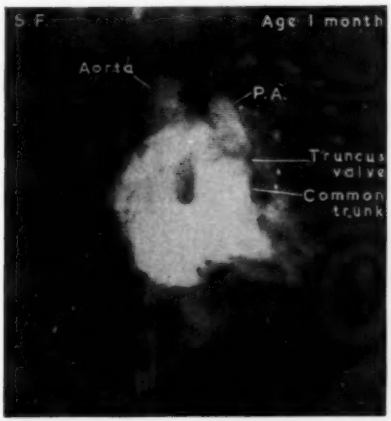

Fig. 38. Persistent truncus arteriosus: S. F., age 1 month. The contrast medium shows filling of the right auricle, right ventricle and a large central trunk giving rise to the aorta and pulmonary artery simultaneously. Confirmed at autopsy.

the pulmonary arteries. Thus the aorta and pulmonary artery fill together. Since the electrocardiogram may show either right or left ventricular hypertrophy, and these children may show much or little cyanosis, the angiogram may be of considerable diagnostic value in differentiating this condition from tetralogy of Fallot and transposition of the great vessels.

Ebstein's Disease

Angiocardiography is risky in Ebstein's disease, since cardiac irregularities or standstill may result during the procedure. Ordinary clinical methods of examination, especially the electrocardiogram, will usually permit a reasonably accurate diagnosis. Cardiac catheterization may prove diagnostic, but may also entail some risk.

Angiocardiography has been carried out on a number of cases of Ebstein's disease, some of which have been reported in the literature. The following anatomic details are outlined: (1) a large right auricle; (2) displacement of the tricuspid valve towards the apex; (3) a lack of a clear outline of a right ventricle; (4) poor filling of the pulmonary artery; (5) the left auricle and left ventricle will fill rapidly when there is a patent foramen ovale.

Atrioventricularis Communis

The following points have been demonstrated in our angiograms in atrioventricularis communis: (1) a large right auricle; (2) a large right ventricle; (3) large, bulging pulmonary artery, usually considerably larger than one sees in other congenital heart anomalies. (4) Pulmonary artery

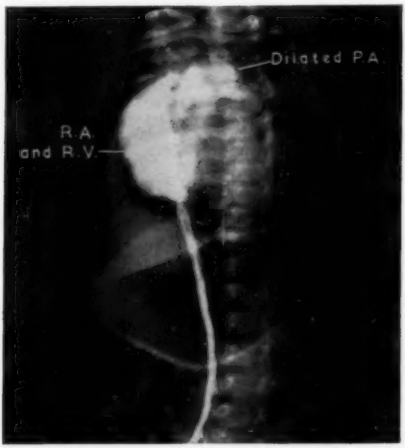

Fig. 39. Atrioventricularis communis: C. G., age 10 months. Large right auricle and right ventricle shown with greatly dilated pulmonary artery. Confirmed at autopsy.

branches are diffusely enlarged and spread out in all directions, indicating a tremendous increase in pulmonary flow. (5) The aorta is usually about normal size, and is often smaller than the pulmonary artery.

These angiograms are usually not diagnostic and simply give indirect evidence of a large left-to-right shunt. See Figure 39.

Patent Ductus Arteriosus

A patent ductus is usually best demonstrated by aortography, but in venous angiocardiography one may occasionally see the ductus clearly. Such has been the case in our experience when the ductus is patent in

pulmonary atresia, and the aorta then delivers a high concentration of contrast medium into the patent ductus. We have also shown a patent ductus in tricuspid atresia by the same technique, and in infantile aortic coarctation or stenosis. (See also under Aortography.)

Ventricular Septal Defect

An angiogram in this anomaly may show an entirely normal heart; however, if the defect is large, there may be evidence of an enlarged pulmonary artery and branches suggesting an increased pulmonary flow. For precise diagnosis cardiac catheterization is usually more useful.

Eisenmenger Complex

In Eisenmenger complex the pressure in the right ventricle is usually approximately the same as systemic, and the right ventricle, pulmonary trunk and branches are enlarged and pulsating. Venous angiocardiography simply demonstrates the enlargement of the right side of the heart and increased caliber of the pulmonary artery and its branches.

If a considerable degree of overriding of the aorta is present, the contrast medium may be seen passing from the right ventricle into the aorta and thus aid considerably in the diagnosis. In most children, however, the shunt into the aorta is minimal and may not be sufficiently developed to be demonstrated by angiocardiography until after twelve to fifteen years of age.

Pure Pulmonary Stenosis

This is a relatively common lesion in its mild form and may not be severe enough to cause enlargement of the right ventricle or interfere in any way with the child's exercise tolerance. However, a large proportion of the children with this defect have a poststenotic dilatation of the pulmonary artery which is usually visible under the fluoroscope. When there is some doubt about this, angiocardiography may demonstrate it with increased clarity. The pulmonary branches are usually not significantly enlarged and do not carry an excessive blood flow. Cardiac catheterization is helpful in determining the height of the pressure in the right ventricle, the pressure in the pulmonary artery beyond the stenosis, and thus aid in making an accurate diagnosis and deciding on whether or not surgical intervention is necessary. However, direct injection of contrast medium into the right ventricle should prove a satisfactory method of revealing the valvular stenosis, and the size of the jet stream through it. Cases for such study should be selected carefully, since the risk should be kept to a minimum.

Auricular Septal Defects

Auricular septal openings may be shown readily if this is the only channel for blood to get into a ventricle, as in tricuspid atresia. In the simple auricular septal defect, however, one may raise the right auricular pressure sufficiently by the injection of the contrast medium to cause it to flow temporarily across into the left auricle. We have demonstrated this occasionally.

A normal patent foramen ovale may sometimes permit an intermittent flow from right auricle to left auricle when a venous angiogram is performed. Here the amount of contrast medium is small and its appearance transient.

AORTOGRAPHY

Aortography is most useful in babies suspected of having patent ductus arteriosus, coarctation of the aorta, aortic hypoplasia or aortico-pulmonary fistula, and occasionally in persistent truncus arteriosus.

Patent Ductus Arteriosus

In patent ductus arteriosus, when the blood flow is from the aorta to the pulmonary artery, the countercurrent procedure for aortography described earlier will demonstrate the presence of the abnormal patency.

An example of an angiogram in a case of patent ductus is shown in Figure 40. The contrast medium can be seen filling the subclavian artery and the aorta. In A the large pulmonary artery can be clearly seen; in *B* the material is spread diffusely through the smaller branches of the lung field; in C a lateral view shows the patent ductus and early filling of the pulmonary main branches.

In infants whose hearts are too small to catheterize readily, this technique has proved valuable. We have had a number of infants in whom heart failure was present or imminent, and the ductus was demonstrated by this technique and subsequently ligated surgically. All these children are alive and well today.

In a typical case of patent ductus arteriosus the continuous murmur is usually present in the pulmonary area. This murmur is often heard in early life even in prematures. It is usually a most reliable sign in leading to an accurate diagnosis. At times, however, there are doubtful cases which lack the characteristic murmur. In a baby with a systolic murmur in the pulmonary area who is noncyanotic the presence of left ventricular hypertrophy in the electrocardiogram is helpful but not diagnostic. If the heart is not large, and there is no evidence of marked elevation of the pulmonary artery pressure, there may be no urgency about an immediate diagnosis. If excessive pressure is present in the pulmonary artery, or if

heart failure is present, diagnosis is important. Here retrograde aortography may prove useful.

The delineation of the ductus arteriosus by an aortogram of course depends on the pressure being higher in the aorta than in the pulmonary

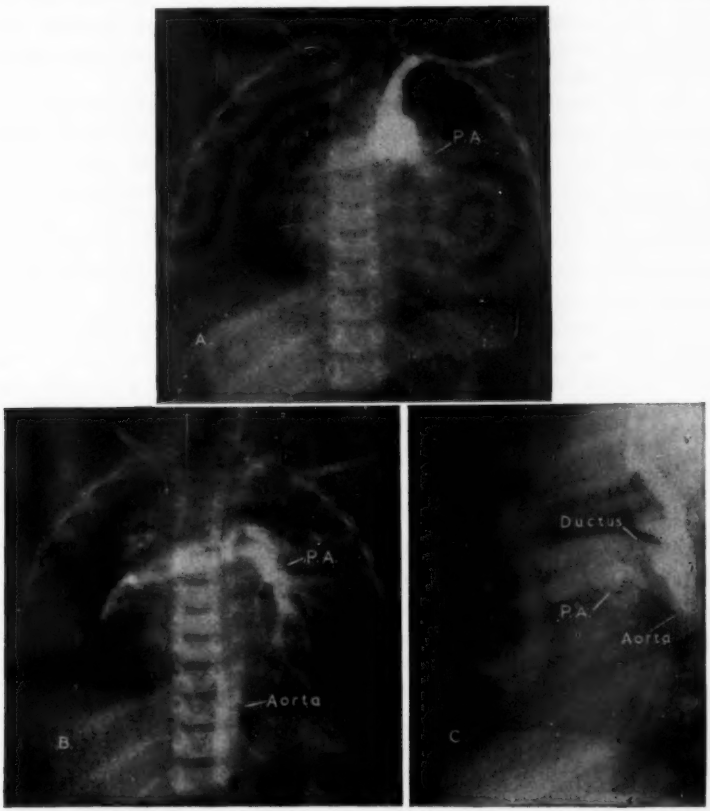

Fig. 40. Patent ductus arteriosus: R. C., age 2 years. *A*, Showing the subclavian artery filled and the contrast medium passing into the pulmonary artery. *B*, The pulmonary trunk branches are filled and at the same time the aorta has filled from the subclavian artery. *C*, The pulmonary artery, aorta and patent ductus are all outlined in the lateral view.

artery. Occasionally the ductus may be patent and the pressure in the pulmonary artery higher than in the aorta, so that the right ventricle is pumping blood out into the descending aorta. Such cases of course cannot be demonstrated by an aortogram. When one suspects a reverse flow through the ductus, the defect can be delineated by venous angiocardiogram.

In most cases of patent ductus arteriosus the ductus is so short that an anteroposterior view, and often a lateral as well, will show overlapping of the pulmonary artery and the aortic shadows, so that the ductus itself cannot be clearly distinguished. However, the fact that the pulmonary artery fills from the aorta is evidence of a patent ductus. Occasionally, when the ductus is unusually long, especially in the lateral view, the pulmonary artery and the aorta may be clearly separated and the ductus visualized with ease.

The differential diagnosis by this method includes aortico-pulmonary fistula or a persistent truncus arteriosus with the aorta giving rise to large pulmonary vessels. We have one angiogram on the latter type of case. One can suspect the diagnosis by the absence of a large normal pulmonary arch and the presence of small pulmonary arteries, apparently rising low on the aortic arch, from the ascending aorta. In many instances, also, persistent truncus arteriosus is accompanied by distinct cyanosis, while patent ductus arteriosus is not.

In aortico-pulmonary fistula the lateral view will show a direct communication between the aorta and the pulmonary artery in the ascending portion of the aorta, rather than the site where the ductus is found on the early part of the descending aorta.

Coarctation of the Aorta

An aortogram is a satisfactory procedure for demonstrating coarctation of the aorta in infants, since the subclavian arises from the aorta close to the site of the coarctation, and almost invariably above it. Thus the aortogram reveals the site and size of the obstruction, and the caliber of the aorta above, and usually below, the coarctation. As seen in Figure 41, it also outlines the collateral circulation to a fair degree.

Since coarctation is a relatively common congenital anomaly, careful search should be made for this defect in any infant presenting any evidence of congenital heart disease. The coarctation may be associated with other defects, but when it is the adult type, it is operable, and operation may be required in the first few weeks of life if failure occurs or there is considerable enlargement of the heart.

Palpation of the femoral arteries is the most important clinical lead to the diagnosis, and should be part of any examination of the heart. In babies the diagnosis is not as easily made as in older children, because the femoral artery may be difficult to feel, even in a normal infant. Blood pressure readings in the arms and legs are most useful, since normally the pressure in the leg should be slightly higher than in the arm in an infant. Frequently the blood pressure cannot be recognized by the use of the stethescope, and we have found an oscillometer of distinct value in forming an opinion of the blood pressures in coarctation of the aorta. Since

such methods usually allow one to arrive at a satisfactory diagnosis, an aortogram is rarely necessary with this defect. Occasionally the pressures may be equivocal, and the surgeon may wish to outline the position and length of the coarctation and the presence or absence, or degree, of aortic hypoplasia, above the coarctation. When such is the case, an aortogram should be performed. Our policy in coarctation has been to postpone operation until ten to twelve years of age. However, in the presence of gross

Fig. 41. Coarctation of the aorta: J. W., age 12 days. Clear-cut coarctation of the aorta is shown with some slight hypoplasia of the aorta above it. Confirmed at autopsy.

cardiac enlargement or heart failure in infants, early operation is required. We have several such patients, one operated on at two weeks of age.

In newborn infants a fair proportion of cases with faint femoral pulsation may have aortic hypoplasia with or without coarctation of the aorta. It is usually a diffuse hypoplasia extending over a considerable portion of the aortic arch. Figure 41 shows segmented hypoplasia in a twelve day old baby. Most similar cases have other associated anomalies that produce early death and make operation impossible. However, some infants with aortic hypoplasia have a sufficiently short area of involvement to permit successful operation.

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CLINICAL CARDIAC CATHETERIZATION IN INFANTS AND CHILDREN

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The purpose of this paper is to discuss the clinical importance of cardiac catheterization, particularly in infants and small children. No attempt will be made to discuss the general subject of cardiac catheterization, since comprehensive review articles are available.[2, 3, 11, 13] The ideas formulated in this study are based largely on an experience of 825 cardiac catheterizations, 188 of which were done in infants from birth to one year of age. The youngest infant was nine days old, the oldest adult sixty-five years.

INDICATIONS

The purpose of cardiac catheterization in infants and children has been twofold: (1) to establish an accurate and specific diagnosis whenever it was considered necessary or advisable; and (2) to determine cardiac dynamics in order to explain, if possible, variations noted in the x-ray or electrocardiographic patterns in certain problem cases. These are broad indications and were interpreted liberally, especially since the procedure could be done easily and practically without risk even in small infants. Furthermore, it was considered that, in general, the earlier a specific diagnosis could be made, the better was the advice that could be given. Hence the number of cardiac catheterizations in small infants. Following this principle has resulted in saving the lives of a number of babies (especially those with patent ductus arteriosus or severe valvular pulmonary stenosis) which might otherwise have been lost, and has spared others from unnecessary operation (particularly exploratory thoracotomy). It has also helped in large measure to fill an important hiatus in our knowledge of the natural history of certain congenital cardiovascular defects.

PREPARATION AND CARE OF THE PATIENT

Up to and including the age of six to eight years, after which premedication was seldom necessary, adequate sedation was usually obtained by the administration of morphine sulfate in the dosage of 1 mg. ($\frac{1}{64}$ grain) per 10 pounds of body weight and sodium phenobarbital, $\frac{1}{2}$ grain per 10 pounds of body weight approximately one-half to one hour before the procedure was started. Occasionally it was necessary to supplement this sedation during catheterization with intravenous Seconal in a dosage of approximately 0.5 to 1 mg. per pound of body weight. General anesthesia was practically never necessary. The personal influence of a kind and gentle nurse was almost as important as the pharmacologic effect of drugs in securing the cooperation of the child. Untoward effects of morphine-sodium phenobarbital sedation occurred in 4 patients—hyperexcitability due to morphine in 3 (all females) and respiratory depression with death, also due to morphine, in a three year old child (Table 9) with primary obliterative pulmonary endarteritis, a condition in which the administration of morphine seems to be particularly dangerous. All patients received parenteral antibiotics prophylactically.

It has not been considered necessary to have continuous electrocardiographic observations routinely during cardiac catheterization, although the equipment is available when necessary. Extrasystoles were often observed fluoroscopically, but were seldom frequent enough or of long enough duration to cause serious concern. Paroxysmal supraventricular tachycardia occurred in 4 cases, and each time reverted to normal sinus rhythm within ten to thirty minutes after administering a full therapeutic dose of digitalis (Cedilanid, 30 micrograms per kilogram) through the catheter, which was withdrawn to the vena cava and left there temporarily for greater ease of drug administration. A fatal ventricular tachycardia occurred once, in a child with severe pulmonary valvular stenosis and marked cardiac enlargement and failure (Table 9). No drugs such as Pronestyl or quinidine were given prophylactically.

TECHNIQUE

The technique of heart catheterization in infants and young children is not essentially different from that in older children and adults. There are, however, certain points of particular interest in the application of this procedure to very small patients. The first is the choice of vein in which to insert the catheter. Though the median basilic vein is usually the choice in older persons, the saphenous vein has proved much more satisfactory in infants and small children (up to the age of five to six years). Even in little babies the saphenous vein will usually accommodate a no. 6 catheter.

Various points of obstruction may be encountered in using this route; these are summarized in Table 1. Having entered the heart via the in-

TABLE 1. *Sites of Obstruction and Their Correction*

SITE OF OBSTRUCTION	TECHNIQUE
Saphenous vein too small	Dissect further and use saphenous bulb—communicating branch between saphenous and femoral. Femoral vein can be used if saphenous not previously ligated
Saphenous admits catheter, but does not permit free motion	Incise vein longitudinally for a distance of 2–3 mm. proximally (toward the heart), thus inserting the catheter into a ⊥-shaped opening. A new incision further toward the femoral may occasionally be necessary
Inability to pass the catheter into the femoral vein (from saphenous)	Isolate and pass temporary ligatures about the major incoming branches to the saphenous, thus helping to direct the catheter tip into the femoral instead of into one of these branches
Obstruction at or near the pelvic brim (iliac vein)	Increase intra-abdominal and venous pressures by manual compression of lower abdomen (after the manner of Crede expression), at the same time manipulating the catheter over the pelvic brim into vena cava
Difficulty in entering innominate vein from left subclavian or superior vena cava from right subclavian	Straight lateral flexion of head toward the side on which the catheter is being inserted. May also require increasing venous pressure as with the Valsalva maneuver.

ferior vena cava, difficulty is occasionally encountered in manipulating the catheter tip into the right ventricle and pulmonary artery. Here experience is the best teacher, but two points of advice may prove helpful: (1) It is sometimes easiest to enter the tricuspid valve by first looping the catheter within the right auricle with the tip directed laterally away from the tricuspid valve, then rotating the entire loop medially, withdrawing slightly until the tip engages in the valve at the inferior border of the right auricle, and then advancing the catheter tip as straight as possible toward the outflow tract of the right ventricle. (2) A stiff catheter is necessary in order to negotiate the angles involved in entering the pulmonary artery from the right ventricle.

These are not by any means the only technical problems, but they are among the most important of those specifically applicable to this particular age group. Adequate discussions of other more general technical problems are to be found in the references.[2, 3, 11, 13]

PROBLEMS OF INSTRUMENTATION

Instrumentation may be as simple or as complicated as necessary for the needs and desires of the investigator. In general, two purposes are served by heart catheterization: (1) to establish a clinical diagnosis, and (2) to study various abnormalities of cardiovascular (and respiratory) physiology. For the latter purpose there is practically no end of functions to be studied, nor of recording devices for their observation. For the former, simplicity and accuracy are the two essential requirements. In attempting to make or confirm a diagnosis by heart catheterization in a sick baby, simplicity of technique as a time-saving element becomes an important factor of safety. It is also important from the practical viewpoint in eliminating the need for extra space, elaborate and expensive equipment, trained personnel, and so forth. Technical simplicity should, of course, not require any sacrifice of practical (not necessarily absolute) accuracy. Nor should elaborate technical devices be considered a substitute for personal skill and experience.

The minimum information considered necessary for establishing a reasonably accurate diagnosis by cardiac catheterization, and some of the requirements for obtaining such information, are enumerated in Table 2.

CLINICAL USES

With certain few exceptions, an accurate differential diagnosis of congenital heart disease may be exceedingly difficult to make clinically in infants. It is in this age group, therefore, that other procedures such as cardiac catheterization have their greatest diagnostic value. Although this is frequently considered to be a difficult age in which to do such proce-

TABLE 2. *Diagnostic Requirements in Catheterization*

DETERMINATION	REQUIREMENTS
Catheter position	Fluoroscopic position, pressure (phasic or mean), oxygen content, relation to next position on advancement or withdrawal of catheter
Pressure relationships	Mean pressure—simple saline manometer; or systolic and diastolic pressures—suitable electronic device. In either case the need for (1) free unobstructed position of catheter tip, (2) immediate visualization of pressure changes, and (3) elimination of artefact
Blood oxygen	(1) Multiple samples; (2) small amount of blood necessary for analysis; and (3) immediate determination
Position of venous-arterial shunt	Auricular—exclusion plus left auricular oxygen unsaturation Ventricular—ventricle-to-face circulation time, direct catheterization of aorta Pulmonary artery-aorta—right brachial and femoral artery oxygen saturations

TABLE 3. *Clinical Results of Catheterization*

AGE	TOTAL NO. OF CASES	OPERABLE DEFECTS											STRUCTURES CATHETERIZED		
		PDA	Coarct.ation	Tetralogy	Pulm. St.	Tricus. At.	% OPERABLE	% MISC.	% INDETERMINATE	% UNSUCCESSFUL	% TOTAL UNDIAGNOSED	DEATHS	Pulm. Art.	Lt. Auric. or Vent.	Aorta
0–6 mo.	120	11	11	5	6	3	30.	40.	22.3	7.7	30.	2	44.5	15.8	16.3
6–12 mo.	68	5	1	12	8	5	45.5	35.3	14.8	4.4	19.2	1	45.6	16.2	19.2
1–3 yrs.	138	6	3	25	13	4	38.7	45.1	11.7	6.5	18.2	1	54.7	10.4	15.8
3–5 yrs.	99	9		10	20		39.5	48.3	8.15	4.05	12.2		70.8	4.1	9.1
5–10 yrs.	101	6	1	14	20		40.6	48.5	8.92	1.98	10.9		80.3	6.9	20.8
10–15 yrs.	51	3	1	9	7		39.3	43.1	11.7	5.9	17.6		72.6	1.98	13.7
15–20 yrs.	31			6	2		25.8	71.	0	3.2	3.2		80.8	0	12.9
20–30 yrs.*	51	3		3	3		17.6	82.4*	0	0	0		96.2	1.98	7.8
30–50 yrs.*	146	2		1	1		0	97.25*	0	1.4	1.4	1	96.	0	0.6
50 yrs. +	20							100.	0	0	0		95.	0	0
Total	825	45	17	85	80	12	29.		11.2	1.9	13.1	5			

* Most of the patients in these age groups were being studied for mitral valve surgery.

dures successfully and safely, it is significant that even in the age group of birth to six months catheterization of the heart, either by itself or in conjunction with other clinical data, provided a definitive diagnosis in 70 per cent of the cases, of which nearly one half (30 per cent of the entire group) were operable (Table 3).

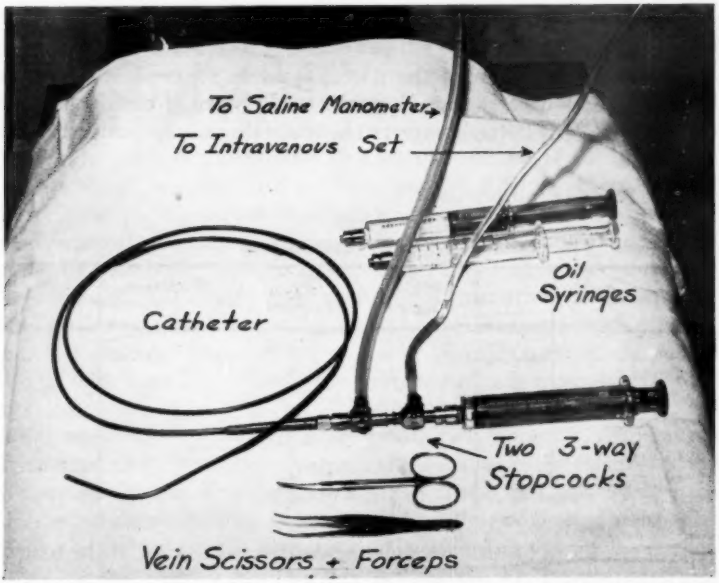

Fig. 42. A simple technical arrangement for satisfactory *clinical* cardiac catheterization. Other requirements, of course, include a fluoroscopy unit and equipment for the determination of blood oxygen contents. Also not shown is an ultraviolet lamp for fluorescein circulation time determinations from the right ventricle.

Patent Ductus Arteriosus

The number of patients catheterized and their age distribution are given in Table 4. Among the indications for cardiac catheterization in this series of patients were the following:

1. The need for establishing a differential diagnosis particularly in the infant group;
2. The desirability of confirming a clinical diagnosis before considering operation;
3. The clarification of atypical features such as unusual murmurs, history of transient cyanosis, electrocardiographic evidence of right ventricular enlargement, and so forth;
4. The evaluation of complicating defects—septal defects, coarctation of the aorta, pulmonary stenosis, and the like;
5. The amplification of a number of specific problems arising in the total program of clinical investigation in the field of congenital cardiovascular disease.

In cases of patent ductus arteriosus cardiac catheterization may be of diagnostic value in several different ways: (1) direct catheterization of the ductus; (2) measurement of an aortic-pulmonary shunt as evidenced by an elevated pulmonary artery oxygen content; and (3) the exclusion of an intracardiac defect (particularly a shunt) with the clinical impression of a patent ductus, but failure to enter the pulmonary artery (Table 4). It is in this latter group that retrograde aortography[10] is of particular value.

Direct catheterization of the ductus is easily accomplished even in little infants. It is important, however, to be wary of certain possible errors, particularly in the interpretation of certain catheter positions. One

TABLE 4. *Patent Ductus Arteriosus*

AGE	NO. OF CASES	DIAGNOSIS BY			MISTAKES
		Cath. of Ductus	PA Oxygen	Exclusion	
0–6 mo.	11	8	2	1	1
6–12 mo.	5	1	4		
1–3 yrs.	6	5	1		2
3–5 yrs.	9	7	1	1	
5–10 yrs.	6	3	3		1
10–15 yrs.	3		3		1
15–40 yrs.	5	1	4		
Total	45	25	18	2	5

type of error is to identify wrongly the great vessel entered at the base of the heart. Such a mistake will not be made if the catheter be advanced well out beyond the cardiac silhouette into the lung in the case of pulmonary artery or beyond the limits of the thorax in the case of aorta. The other error is to misinterpret the route by which the aorta is entered. Methods for preventing this mistake will be suggested.

Clinically, the two most important conditions to be differentiated from patent ductus arteriosus are (1) aortic-pulmonary septal defect and (2) high interventricular septal defect, usually with pulmonary hypertension. In the first the passage of the catheter into the aorta through the defect instead of through a ductus may be differentiated in the left anterior oblique or lateral view, the catheter entering the aorta anteriorly in the former situation and more posteriorly in the latter.[1] With a high interventricular septal defect the catheter may pass into the aorta directly from the left ventricle instead of from the pulmonary artery. This situation can usually be properly evaluated by recording pressure variations continuously and visualizing the catheter position while carefully withdrawing into the right ventricle. In the case of a patent ductus, unless the aortic and pulmonary artery pressures are nearly identical, the retro-

grade course of the catheter from aorta through ductus into pulmonary artery and right ventricle may be positively identified. Another manipulation of positive diagnostic value is to pass the catheter out into the right or left main pulmonary artery and into the aorta through the ductus without withdrawing from the main pulmonary artery into the right ventricle.

There is more opportunity for error if one relies solely on oxygen differences between the right ventricle and the pulmonary artery. One such error is to miss a small ductus with an oxygen difference within arbitrary limits of normal or to miss even a large ductus (1) in combination with an interauricular or an interventricular septal defect or (2) with sufficient pulmonary hypertension to reduce the volume of the aortic-pulmonary shunt. Another error is to misdiagnose a ductus when a higher than normal pulmonary artery oxygen is in reality due to a high interventricular septal defect or an incomplete aortic-pulmonary septum. The exact differentiation between these various conditions may be exceedingly difficult, and usually requires a careful correlation of all available clinical data plus contrast roentgenography and even occasional exploratory thoracotomy. Diagnosis by exclusion (a misnomer, of course) is fraught with too many difficulties to warrant anything more than passing mention.

The recording of pulmonary artery pressure has more than simple diagnostic importance in suspected patency of the ductus arteriosus. Especially in patients with the clinical signs of a patent ductus, in whom the electrocardiogram shows definite or even questionable evidence of right ventricular hypertrophy, it is important to know before operation whether or not the ductus is compensating for an associated pulmonary stenosis. A lower than normal pulmonary artery pressure (in relation to right ventricular pressure) will provide evidence of this defect even in the presence of a patent ductus. Such was the case in 4 children of this series, 2 of whom were preoperative and 2 postoperative tetralogies. The detection of a complicating coarctation of the aorta by catheterization alone is a little more difficult unless pressures can be determined on both sides of the coarctation after passing through the ductus from the pulmonary artery.

Coarctation of the Aorta

Coarctation of the aorta is usually a clinical or a roentgenographic diagnosis, with few indications for cardiac catheterization except perhaps in complicated cases. However, physiologic information has added significantly to a better understanding and consequently better management of certain clinical problems. The major contribution of heart catheterization, correlated with other clinical data, is a clarification of the relation

TABLE 5. *Coarctation of the Aorta (Ductus Closed at Birth)*

	POSITION OF FETAL DUCTUS	
	Proximal to Coarctation	Distal to Coarctation
Heart size at birth	Right ventricle enlarged	Normal
Infant electrocardiogram	RVH—Rt. BBB	Normal—LVH
Heart failure	Present at birth	Absent at birth
	Retrogressive	Progressive
	Good response to medical treatment	Poor response to medical treatment
Collateral circulation at birth	Probably well developed	None
Prognosis	Excellent	Poor
Time to operate	Choice, 2–6 years	Immediate, with temporary shunt
Physiologic:		
Right intracardiac pressures	Normal	Increased (left-sided failure)

between coarctation of the aorta and the position of the fetal ductus arteriosus.[16] These are summarized in Table 5.

Tetralogy of Fallot

The clinical syndrome of tetralogy of Fallot, based on history, physical examination, electrocardiographic and fluoroscopic information, is usually easily recognizable and not frequently mistaken for other cyanotic defects. In making this diagnosis clinically, only two basic types of errors can be made: (1) an incorrect estimation of pulmonary pressure and blood flow, and (2) a miscalculation of the location of the intracardiac venous-arterial shunt. In the first instance the differentiation between tetralogy

TABLE 6. *Tetralogy of Fallot*

AGE	TOTAL NO. OF CASES	DIAGNOSTIC TYPES		
		I	II	III
0–6 mo.	5		2	3
6–12 mo.	11	1	2	8 (1 mistake)
1–3 yrs.	25	3	4	18
3–5 yrs.	12		4	8
5–10 yrs.	14	4	7*	3 (1 mistake)
10–15 yrs.	9	3	4	2 (1 mistake)
15–30 yrs.	9	4	5	
Total	85	15 (18.3%)	28 (34.2%)	42 (47.5%)

I = Catheterization of right ventricle, pulmonary artery and aorta.
II = Catheterization of right ventricle and pulmonary artery, short ventricle-to-face circulation time.
III = Clinical pulmonary stenosis, catheterization of aorta or short ventricle-to-face circulation time.
* Two of these cases required angiocardiography.

and transposition of the great vessels without pulmonary stenosis, or Eisenmenger's complex, is involved; in the second, the differentiation between tetralogy and pulmonary valvular stenosis with closed interventricular septum and a patent foramen ovale or an interauricular septal defect is the problem. By cardiac catheterization these diagnostic errors may be decreased or eliminated by proving the presence of pulmonary stenosis, dextroposition of the aorta (over an interventricular septal defect), or a combination of the two.

The relative frequency with which the various types of catheterization data may be obtained in a representative series of patients with surgically proved tetralogy of Fallot is indicated in Table 6. It is important to note that the only diagnostic errors occurred with failure to enter the pulmonary artery, pulmonary hypertension being discovered at operation in

each of these 3 patients. An equal number of patients of about the same ages were thought clinically to have pulmonary hypertension because of pulmonary artery pulsations observed fluoroscopically, but were found on heart catheterization to have pulmonary hypotension and tetralogy of Fallot. Only 2 of the 43 patients in whom the pulmonary artery was entered had indeterminate ventricle-to-face circulation times and required angiocardiography to prove the presence of aortic dextroposition. Three other children, whose hearts were not catheterized, were thought clinically to have tetralogies, but proved to have pulmonary valvular stenosis with intact ventricular septum and auricular septal defect. The value of cardiac catheterization data is thus evident.

The question will probably be asked: What cyanotic patients should be selected for diagnostic cardiac catheterization? There can be no standard answer. However, certain principles derived from this study provide at least a partial solution to the problem. Granted that unless all available studies are done on all patients there will inevitably be an occasional diagnostic error, such a routine procedure would hardly prove practicable. (It is also important to note that the mortality associated with surgical exploration has not been high.) Certain deviations from standard diagnostic patterns, particularly requiring the differentiation between operable and inoperable or between the need for different types of operations (i.e., shunt versus direct valvulotomy), must therefore serve as indications for such additional studies as cardiac catheterization and occasionally angiocardiography.

Considering tetralogy of Fallot as the basic diagnosis, some of the more commonly encountered variations serving as suitable indications for cardiac catheterization might be listed to include dyspnea out of proportion to cyanosis, the presence of a diastolic or a continuous rather than just a systolic murmur, unusual prominence or fluoroscopically visible expansile pulsations of the main branch pulmonary arteries, moderate to marked cardiac enlargement, especially with unusual prominence of the upper left middle segment, almost any electrocardiographic variations from the pattern of uncomplicated right ventricular enlargement, and perhaps others. Most of the differential diagnoses involved depend upon measurements from the pulmonary artery, so that with respect to the tetralogy of Fallot one has at least a 50 per cent chance of getting the necessary information by cardiac catheterization (Table 6, columns I and II). Failing to enter the pulmonary artery, one may still have recourse to angiocardiography or surgical exploration.

Pulmonary Stenosis

The clinical problems for which cardiac catheterization was done in this group of infants and children with pulmonary stenosis (exclusive of

TABLE 7. *Syndromes Resulting from Pulmonary Stenosis*

	IDIOPATHIC DILATATION OF PULMONARY ARTERY, OR MILD PULMONARY VALVULAR STENOSIS	MILD TO MODERATE PULMONARY VALVULAR STENOSIS (CLOSED SEPTA)	MODERATE TO SEVERE PULMONARY STENOSIS (CLOSED SEPTA)
Basal systolic murmur	+	+	+
Physical disability	0	0-slight	Marked
Cardiac failure	0	0	+
Cyanosis	0	0	Only with auricular shunt
Liability to SBE	Probably 0	+	?
Oxygen consumption (standard exercise test)	Increase (normal)	Increase-less than normal	Decrease
Heart size—X-ray	Normal	Normal–slight increase	Variable–marked enlargement
Pulmonary vascularity	Normal	Normal Prominent main pulmonary artery	Decrease peripherally Poststenotic dilatation
Electrocardiogram	Normal or uncomplicated right bundle branch block	Right ventricular hypertrophy	Right ventricular hypertrophy plus right bundle branch block
PA pressure	Normal–slight decrease	Slight–moderate decrease	Marked decrease
RV pressure	Normal	Slight–moderate increase	Marked increase
Central venous pressure	Normal	Normal	Increase
Indications for operation	0	?	+

tetralogy of Fallot) included the following: (1) the differential diagnosis of noncyanotic congenital cardiac defects characterized by a systolic murmur, particularly with electrocardiographic evidence of right bundle branch block or right ventricular hypertrophy; (2) the determination of the presence and the severity of pulmonary stenosis in cases with closed septa (noncyanotic); (3) the determination of the presence or absence of an associated intraventricular venous-arterial shunt—i.e., dextroposition of the aorta, in patients with pulmonary stenosis and cyanosis; (4) the exact location, if possible, of the stenotic area, i.e., valvular or infundibular; and (5) comparison of preoperative and postoperative data for the assessment of the success of surgical techniques.

Cardiac catheterization, in this study as in others, has proved that pulmonary stenosis with closed septa is one of the most common of the

TABLE 8. *Pulmonary Stenosis (with Closed Ventricular Septum)*

AGE	TOTAL NO. OF CASES	PULM. ARTERY CATHETERIZED	RIGHT VENTRICLE	MISTAKEN DIAGNOSIS	INFUNDIBULAR STENOSIS
0–6 mo.	6	4 (66.6%)	2	1	
6–12 mo.	8	4 (50.0%)	4	1	1
1–3 yrs.	13	9 (69.2%)	4		1
3–5 yrs.	20	16 (80.0%)	4	1	1
5–10 yrs.	19	16 (84.3%)	3		1
10–15 yrs.	7	7 (100%)			1
15–30 yrs.	7	7 (100%)			1
Total	80	63	17	3	6

noncyanotic defects. It has also helped clarify what are now easily recognizable clinical syndromes resulting from varying degrees of severity of this abnormality (Table 7).

The pulmonary artery was not actually entered in a number of patients (Table 8). These were cases of severe pulmonary stenosis, and failure to catheterize the pulmonary artery was for three principal reasons: (1) With a closed ventricular septum it is dangerous to obstruct further the already tiny opening into the pulmonary artery. (2) There is apparently an increased danger of fatal ventricular arrhythmias resulting from manipulation of the catheter within a greatly enlarged and failing right ventricle. The only death in this entire series of patients *directly* attributable to cardiac catheterization occurred in just such a case. For these two reasons catheterization of the pulmonary artery was not even attempted in such cases. (3) In the presence of severe right ventricular hypertension and especially with tricuspid insufficiency, it is extremely difficult to even keep the catheter within the right ventricle, much less manipulate it into the pulmonary artery.

Failure to catheterize the pulmonary artery allows for one important error in clinical diagnosis, namely, the differentiation between pulmonary stenosis and primary obliterative pulmonary endarteritis. Both may have

a systolic murmur, right-sided congestive heart failure, a grossly enlarged heart with right ventricular hypertrophy and right auricular dilatation, dilated main pulmonary artery and major branches, but clear peripheral lung fields, decreased oxygen consumption on standard test exercise, and long ventricle-to-face circulation time. The only possible difference may be pulmonary hypertension in one and hypotension in the other; if the pulmonary artery cannot be catheterized, it may remain to surgical exploration to establish the differential diagnosis. Such was the case in one

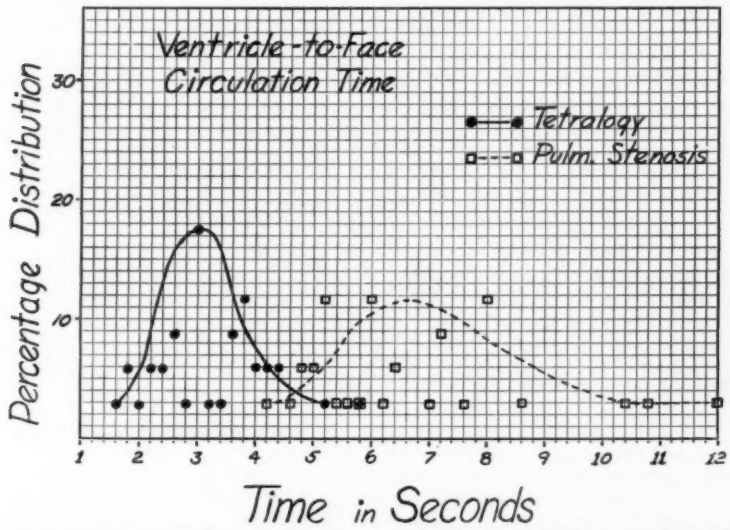

Fig. 43. Ventricle-to-face circulation time determinations in tetralogy of Fallot and pulmonary valvular stenosis with closed ventricular septum. Sixty-eight cases are represented, 34 in each group. The only overlapping other than the 2 cases of tetralogy which required angiocardiography are in the region of 4–4½ seconds. It is probably significant that the 2 patients with pulmonary valve stenosis and relatively short circulation times were less than 2 years old, while the 2 cases of tetralogy with longer circulation times were 7 and 9 years of age.

child in this group of cases. Angiocardiography is particularly dangerous in primary pulmonary hypertension, resulting not infrequently in sudden death, probably from acute cor pulmonale.

Assuming, as probably correct, that angiocardiography bears a higher risk of mortality than heart catheterization, the differentiation between tetralogy and pulmonary stenosis with intact ventricular septum can more safely and just as accurately be determined by the ventricle-to-face circulation time with fluorescein (Fig. 43). This has already been discussed,[14] but one additional comment seems appropriate. Instead of comparing the circulation times in these two conditions with normal, which results

in an annoying overlapping of figures, they should be compared against each other, with pulmonary stenosis as the common factor, and presence or absence of a right ventricle-aortic shunt as the variable. This provides a more distinct differentiation of the two conditions. The degree of prolongation of the ventricle-to-face circulation time in pulmonary stenosis with closed interventricular septum is not a suitable index of the severity of the pulmonary obstruction.

The preoperative differentiation between valvular and infundibular pulmonary stenosis is important but difficult. This has been attempted by the pattern of systolic and diastolic pressure variations as the catheter is withdrawn from the pulmonary artery.[13] In this series of patients a similar attempt was made by visualizing the position and movement of the catheter simultaneously with changes in mean pressure as the catheter was withdrawn from the pulmonary artery. Valvular stenosis could occasionally be determined by a sudden increase of pressure immediately below the valve area, the catheter at the same time moving freely within the right ventricle. Infundibular stenosis could sometimes be certainly determined by withdrawing the catheter tip through a long segment of the right ventricle with continuously low pressure and lack of free motion of the catheter. Of course there were also instances in which one could just not be at all sure as to the site of the stenotic region.

The physiologic and clinical results of pulmonary valvulotomy of the Brock type have uniformly included the following:

1. Increased pulmonary artery pressure and blood flow, when this could be measured preoperatively and postoperatively;
2. Decreased right ventricular pressure;
3. Decreased right auricular pressure when this was elevated preoperatively;
4. Loss of cyanosis when this was present preoperatively;
5. Increased left auricular pressure when this could be measured by catheterizing the left auricle through a patent foramen ovale;
6. Decreased heart size;
7. Disappearance of congestive heart failure when this was present preoperatively;
8. Electrocardiographic changes questionable;
9. Usually no appreciable change in the quality of the heart murmur.

The ease with which the left auricle can be catheterized through a patent foramen ovale in this age group, the frequent reversal of the usual pressure gradient between the right and left auricles, and the changes of pressure in these chambers after operation, all suggest that such measurements may be of confirmatory value as physiologic evidence of pulmonary stenosis, especially in patients in whom the right ventricle and pulmonary artery cannot be catheterized without difficulty or danger. The possibility would seem to warrant further investigation, particularly from the viewpoint of establishing the necessary criteria and of differentiating, if possible, pulmonary stenosis from primary pulmonary hypertension.

Tricuspid Atresia

Tricuspid atresia is largely a clinical (including electrocardiographic and roentgenographic) diagnosis. However, since this is not the only congenital defect which combines cyanosis and left ventricular enlargement, cardiac catheterization is occasionally justified as a diagnostic procedure. The typical catheterization findings are (1) inability to enter the right ventricle, (2) relative ease of entering the left auricle and left ventricle, and (3) oxygen unsaturation in the left auricle indicating a right-to-left shunt at this level. It would be highly valuable to be able to determine whether the auricular shunt were through an actual auricular septal defect or simply through a patent foramen ovale. As yet, however, this does not seem practicable.

Rarely during infancy tricuspid atresia may occur in combination with a patent ductus arteriosus. The differentiation between this and uncomplicated patent ductus arteriosus is, of course, extremely important from the viewpoint of avoiding surgical closure of the ductus in the former and the necessity of the operation in the latter. Although both conditions are characterized electrocardiographically by left ventricular hypertrophy, the characteristic pattern of a short PR segment and broad QRS interval with absence of a Q wave in leads from the left side of the precordium will raise the suspicion of tricuspid atresia,[17] which may then be confirmed by cardiac catheterization or by catheterization and angiocardiography.

CLINICAL CORRELATIONS

As with most if not all other laboratory procedures, one of the major contributions of cardiac catheterization, other than for its direct diagnostic value, is to be derived from its correlation with other clinical and laboratory data. One such correlation is that of right ventricular mean pressure with the pattern of the electrocardiogram, particularly in the precordial leads. With the single exception of uncomplicated coarctation of the aorta in infants in whom the aortic insertion of the fetal ductus was proximal to the coarctation[16] (Table 5), there was a positive correlation between elevation of the right ventricular mean pressure and electrocardiographic evidence of right ventricular hypertrophy (frequently without roentgenographic evidence of enlargement of this chamber). This information has been of particular importance in estimating the need for operation in infants with this defect. The relationship between right ventricular pressure and the precordial lead electrocardiogram has also given promise of providing a differentiation between the pattern of right bundle branch block with a normal and that with an enlarged right ventricle and possibly even that of right bundle branch block with left ventricular hypertrophy. This is a problem on which considerable work needs

to be done, but, if practicable, the additional clinical value of the electrocardiogram will obviously be great.

Another type of correlation has been that of the various clinical and physiologic features of patent ductus arteriosus. Of particular importance are those features which have helped clarify the syndromes of patent ductus arteriosus in infancy and early childhood[15] and with pulmonary hypertension at any age.[8] For example, the characteristics of the murmur of patent ductus (or even the presence of any murmur) depend on the ratio between aortic and pulmonary artery pressures. The significance of this relationship has placed particular emphasis on the importance of the pulmonary arterial pressure, the relatively high level of which during infancy correlates positively with the anatomic finding of relative hyperplasia of the media of the pulmonary arterioles in this age group.[5, 6] This in turn would appear to clarify further the clinical importance of other congenital cardiac defects associated with a left-to-right shunt during the first six to twelve months of infancy.

A third type of correlation, previously mentioned, is that of physiologic data with unusual electrocardiographic or roentgenologic patterns in children suspected of having some type of heart disease. Though heart catheterization does not necessarily provide the ultimate information about the anatomy of the heart, it is capable in many instances of demonstrating normal function and thus allaying any apprehension derived from a possibly erroneous suspicion of cardiac enlargement. As already stated, cardiac catheterization may also provide a satisfactory explanation for what might otherwise be considered an important murmur by demonstrating, for example, benign idiopathic dilatation of the pulmonary artery (Table 7).[4, 7, 9]

INDETERMINATE AND UNSUCCESSFUL RESULTS

An analysis of failures and mistakes should be helpful in improving the accuracy and clinical usefulness of cardiac catheterization. Actually, the number of unsuccessful heart catheterizations was small—a total of 2 per cent in the entire series and a maximum of less than 10 per cent in the age group of birth to six months (Table 1). The reason for most of these failures was obstruction within the venous system, suggestions for the correction of which have already been made (Table 2). The largest group in which improvement must be sought is that in which the clinical diagnosis could not be made even after a technically successful procedure. The reasons for these indeterminate results are multiple and do not necessarily reflect technical inadequacies. With liberal case selection, for example, there must be an indeterminate number in whom a clinical diagnosis never could be established by right-sided cardiac catheterization, no matter what technical improvements should be made. Among

such diagnoses would be included primarily but not exclusively the left-sided cardiac defects. Next, there are probably many cases with septal defects so small that their detection by oxygen differences is virtually impossible. In these cases such techniques as multiple blood oxygen sampling, dye dilution curves and perhaps others should help to make such diagnoses possible. On the other hand, the making of such diagnoses as these will in most instances have little clinical importance anyway. The more important thing will be to demonstrate the fact that there is little if any alteration in cardiac physiology, which can easily be done with present techniques.

TABLE 9. *Deaths during Catheterization*

AGE	DIAGNOSIS	CAUSE OF DEATH
3½ wks.	Coarctation of the aorta and mitral atresia	Congestive heart failure
11 wks.	Cyanotic—no autopsy	Died before actual catheterization; anoxia plus sedation
2 yrs.	Severe pulmonary valvular stenosis, in failure	Ventricular arrhythmia
3 yrs.	Primary obliterative pulmonary endarteritis	Died before catheterization, respiratory depression probably from morphine
34 yrs.	Mitral and aortic rheumatic valve disease, in severe failure	Febrile chill and collapse, congestive heart failure

Total mortality—5 cases, 0.6%

The deaths and their possible causes are listed in Table 9. All were patients with severe heart disease, in whom almost any incident, no matter how trivial, might well have had a fatal result. No serious complications have occurred thus far in patients with less severe heart disease, and fortunately few even in the serious group. It may therefore be concluded that over a wide range of clinical experience, with respect both to age and type of heart disease, the slight risk involved (though there *is* a risk) makes cardiac catheterization a well justified diagnostic procedure.

Mention should also be made of a recent therapeutic application of cardiac catheterization. This is the successful performance of a pulmonary valvulotomy using a specially constructed catheter tip.[12] Whether or not this will eventually supplant transthoracic surgery for pulmonary valvular stenosis remains, of course, to be determined.

SUMMARY AND CONCLUSIONS

1 Cardiac catheterization can be done safely and successfully at all ages, even during early infancy.

2. Especially in infants and young children, catheterization of the heart is done under morphine-sodium phenobarbital sedation, using the saphenous system.

3. In patent ductus arteriosus the diagnosis may be made by catheterizing the ductus itself or by establishing the presence of an aortic-pulmonary shunt as evidenced by an elevated pulmonary artery oxygen. Possible errors in diagnosis, and means for their prevention, are outlined.

4. The two different syndromes of coarctation of the aorta in infants, depending on the site of the aortic insertion of the fetal ductus, are summarized.

5. Catheterization of the heart is of practical value in differentiating the various cyanotic defects, particularly tetralogy of Fallot and pulmonary valvular stenosis with closed intraventricular septum. The value of catheterizing the pulmonary artery and the aorta and the importance of the ventricle-to-face circulation time are stressed.

6. Clinical and physiologic characteristics of the various syndromes associated with pulmonary valvular stenosis are outlined.

7. Cardiac catheterization has proved that the Brock operation for valvular pulmonary stenosis has been highly successful in most cases.

8. Catheterization of the heart is only of confirmatory value in tricuspid atresia.

9. Certain clinical correlations of cardiac catheterization are outlined, especially the relationship between right ventricular mean pressure and the form of the ventricular deflections in the precordial lead electrocardiogram.

10. The indeterminate and unsuccessful catheterization cases were analyzed in an effort to improve the accuracy and clinical usefulness of the procedure.

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DIAGNOSIS OF CONGENITAL CARDIOVASCULAR MALFORMATIONS UNACCOMPANIED BY CYANOSIS

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The traditional clinical classification of congenital cardiovascular malformations includes two major divisions: those accompanied by cyanosis, and those not accompanied by cyanosis. Such a classification is of limited value to the physician confronted with an individual child, since the second group comprises a large variety of conditions, some of which are unimportant and some of which may result in severe symptoms and death. Accurate identification of the anatomic abnormality is important from the standpoint of handling the patient, advising the parents, outlining treatment and determining prognosis.

In recent years special methods of diagnosis have been developed which have clarified our understanding of the physiology of congenital heart disease and have redefined diagnostic criteria based on interpretation of physical, roentgenographic and electrocardiographic signs of the various types of anomalies seen in infants and children. In the noncyanotic cases cardiac catheterization has been of greatest value. Retrograde aortography, angiocardiography, direct tracings of arterial pressure, oximetry, arterial dilution curves of injected dye, calculations of systemic and pulmonary blood flow, and studies of cardiac output have all contributed to the increasing knowledge in this field. Since most of these procedures require elaborate technical equipment, available only in large medical centers, this discussion will, for the most part, be limited to the usual methods of diagnosis available to any physician.

It is convenient to divide the types of noncyanotic congenital malfor-

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mation of the heart into two main groups based on the fact that the altered physiology and work of the two sides of the heart produce changes which can be detected clinically, roentgenologically and electrocardiographically: (1) conditions resulting in increased load on the left ventricle with possible left ventricular failure and (2) conditions causing increased work and possible failure of the right ventricle. Such a working classification has proved of value, although there is some overlapping between the two groups, and there are limitations to its application.

GROUP 1. CONDITIONS CAUSING INCREASED LEFT VENTRICULAR WORK

There are several types of congenital anomalies of the heart and great vessels that may lead to left ventricular failure with resultant pulmonary congestion and edema in infants. Patent ductus arteriosus, ventricular septal defect, coarctation of the aorta, stenosis of the aortic valve, subaortic stenosis, endocardial sclerosis, cardiac type of glycogen storage disease, and anomalous origin of the left coronary artery from the pulmonary artery are the most important examples. Infants with left ventricular failure, regardless of cause, have certain symptoms in common which should direct the attention of the physician toward one of the conditions mentioned. Poor appetite, failure to gain weight, irritability, restlessness, rapid respiration and dyspnea are frequent complaints. Cardiac enlargement, pulmonary congestion, and radiographic and electrocardiographic evidence of left ventricular enlargement are common findings. The characteristics of these conditions will be discussed briefly.

Patent Ductus Arteriosus

Patent ductus arteriosus is often considered to be a relatively benign anomaly in infants, causing little or no trouble until several or many years have passed. The complications of subacute bacterial endocarditis or pulmonary hypertension with right ventricular strain are not expected to occur until adolescence or adult life.

Although most infants with patent ductus arteriosus have no symptoms, there are exceptions. If the opening is large, there may be a large shunt of blood from the aorta to the pulmonary artery, causing an increased volume of blood to pass through the lungs, the left atrium and the left ventricle with resultant increase in the work of the left ventricle. Cardiac enlargement, congestive failure with pulmonary edema, and death have occurred in infants with this anomaly uncomplicated by any other abnormality. By careful examination and interpretation of the auscultatory findings, peripheral pulse, and radiographic and electrocardiographic signs, the existence of a patent ductus arteriosus can be suspected in many of these infants.

Clinical features of a large patent ductus in infants are a large, overactive heart with a strong apical thrust, a blowing systolic murmur in the pulmonic area with extension toward the left clavicle, accentuation and reduplication of the second cardiac sound in the pulmonic area, and a bounding peripheral pulse. Occasionally a diastolic murmur is audible in the first year of life, but this is rare. Roentgenographic and fluoroscopic findings consist in cardiac enlargement with evidence of enlargement of

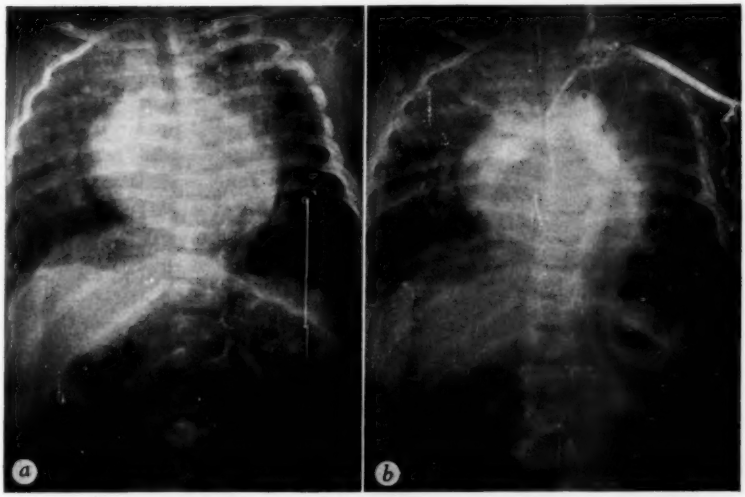

Fig. 44. Eight month old girl with a large heart, episodes of pulmonary congestion, and a systolic murmur in the upper left sternal area. Scout roentgenogram, *a*, and aortogram, *b*, showing communication between the aorta and the pulmonary arteries. Note the large pulmonary arteries. A large patent ductus was found at operation. After closure of the ductus the heart returned to normal size, and the child is normal to examination.

the left ventricle, and increased pulmonary vascular markings with increased pulsation of the main pulmonary arteries. Electrocardiographic features are evidence of left ventircular hypertrophy or less right ventricular predominance than is usual in early infancy.

If all the characteristics mentioned are present, the diagnosis can be suspected without further investigation. If there is doubt because of findings which are not typical, retrograde aortography can be performed with little risk to the patient, and the communication between the aorta and the pulmonary artery can be demonstrated (Fig. 44). Although cardiac catheterization studies can be done, general anesthesia is usually necessary, and the risk to life is thereby increased. The following case illustrates this fact.

An infant boy aged 10 months was admitted to the hospital with a history of irritability, rapid respiration and pallor beginning one month before. Examination revealed an ill baby who was dyspneic at rest and exhausted after feedings. The heart was enlarged and overactive, there was a loud systolic murmur at the pulmonic area, and pulsations in the femoral artery were strong. Radiographic examination of the thorax showed cardiac enlargement and increased pulmonary vascular markings (Fig. 45, *a*). Left ventricular hypertrophy was demonstrated by electrocardiographic tracings (Fig. 45, *b*). Because patent ductus arteriosus was suspected, cardiac catheterization was performed under tribromoethanol (Avertin) anesthesia with confirmatory results.

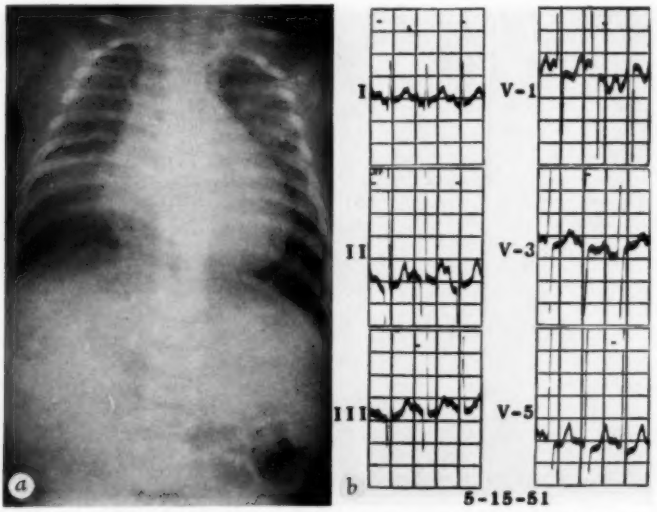

Fig. 45. *a*, Cardiac enlargement and increased pulmonary vascular markings are evident. *b*, Left ventricular hypertrophy is demonstrated.

Dyspnea increased and cyanosis followed. The baby died in spite of vigorous supportive measures. Patent ductus arteriosus, pulmonary congestion and hemorrhage, and left ventricular hypertrophy were found at autopsy.

Diagnosis of patent ductus arteriosus in children past the age of two or three years is based primarily on the presence of a continuous, machinery-like murmur with systolic accentuation located in the pulmonic area, in addition to the collapsing peripheral pulse, roentgenographic evidence of increased blood flow through the lungs and electrocardiographic evidence of left ventricular hypertrophy or biventricular hypertrophy. Pulmonary hypertension may develop in midchildhood or late childhood, although this complication usually is delayed for many years. When it occurs, the diastolic phase of the murmur may diminish and eventually disappear, and reversal of the flow of blood through the ductus may occur during some phase of the cardiac cycle. Cyanosis may then be noted.

Ventricular Septal Defect

Though a defect in the ventricular septum is one of the most common types of congenital heart disease, it is not generally recognized that this anomaly is serious and may cause death in the first few months of life. In the usual case of ventricular septal defect there is a shunting of blood from the left ventricle into the right ventricle, owing to the difference of pressure between the two ventricles. There is resultant increase in flow of blood through the pulmonary system and an increased return of blood to the left side of the heart. Thus there is an increased load on the left ventricle, although the right ventricle also participates in the additional work if the septal defect is in the muscular portion of the septum. With a large defect and a large shunt, failure of the left ventricle may occur in infancy before the heart adjusts to the altered dynamics of the circulation. Study of pathologic material indicates that 40 to 60 per cent of infants with this anomaly die before reaching the age of one year. Those infants who adjust to the excess pulmonary flow frequently survive for many years without much disability. This is particularly true in those cases in which the septal defect is small, with relatively little flow from the left to the right ventricle.

The diagnosis of a sizable ventricular septal defect in infants can often be made by careful analysis of the physical, roentgenologic and electrocardiographic findings, but there is frequently difficulty in distinguishing this condition from patent ductus arteriosus, since the functional changes are similar in the two anomalies. If failure of the left ventricle occurs, the usual symptoms are present. The heart is large and overactive. The murmur is usually loud and blowing, systolic in time, of maximal intensity just to the left of the midportion or lower portion of the sternum, and is transmitted toward the apex and left axilla, but not extending toward the left clavicle. A systolic thrill is present in most cases. The second heart sound in the pulmonic area may be normal or accentuated. The peripheral pulse is not collapsing. The heart is enlarged, and the pulmonary vascular markings are increased as seen on radiographic examination. Electrocardiographic evidence of left ventricular hypertrophy or biventricular hypertrophy is usually present.

The following is an example of an infant with a large ventricular septal defect that resulted in cardiac failure and death.

A 2½ month old boy was admitted to the hospital with a history of atelectasis in the first 2 weeks of life treated with aspiration of the bronchus. At the age of 6 weeks he was dyspneic and had occasional bouts of cyanosis with feedings or when crying. Administration of oxygen was necessary. Physical examination revealed dyspnea and cyanosis, rales and diminished breath sounds on the right. There was tachycardia, and a systolic murmur was noted in the lower sternal area. Femoral pulsations were good. Radiographic examination of the thorax showed cardiac enlargement and pulmonary congestion (Fig. 46). The electrocardiogram suggested enlargement of both left and right ventricles. Digitalis and oxygen were administered, but the infant failed

to improve and died within a few days. Postmortem examination disclosed a defect in the membranous portion of the ventricular septum and severe pulmonary congestion.

If ventricular septal defect cannot be differentiated from patent ductus arteriosus by the usual diagnostic methods in an infant with cardiac enlargement, special investigation should be undertaken, since the latter condition can be successfully treated surgically, and delay in operation

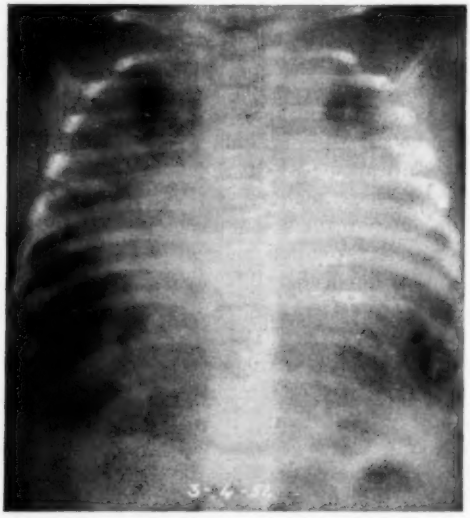

Fig. 46. Cardiac enlargement and pulmonary congestion.

may prove fatal. Cardiac catheterization is the most exact and reliable procedure, but the risk of general anesthesia must be considered. Retrograde aortography is of value in excluding a diagnosis of patent ductus and is recommended, since it causes little risk to the patient and is less difficult technically than cardiac catheterization.

Coarctation of the Aorta

Coarctation of the aorta is usually classified as infantile or adult in type. Such a division is not helpful in understanding the condition and the altered physiology. A better basis for classification is the anatomic relation of the coarctation to the location of the ductus arteriosus. The constriction of the aorta may be proximal or distal to the ductus. When the coarctation is proximal to the ductus, the fetal circulation is essentially normal, since the left ventricle supplies blood to the head and neck while the right ventricle supplies the major portion of the blood to the descending aorta through the ductus. This is the so-called infantile type.

There is no stimulus for the development of collateral channels, since the descending aorta receives adequate amounts of blood. After birth the ductus usually closes and the blood flow to the descending aorta is shut off. This results in a sudden strain on the left ventricle, and decompensation may occur before collateral channels develop.

When the coarctation is distal to the ductus (the so-called adult type), the fetal circulation is different from normal in that the pulmonary artery does not communicate with the descending aorta, but both the left ventricle by means of the ascending aorta and the right ventricle by means of the ductus communicate with the aorta proximal to the constriction. In this situation the stimulus for collateral circulation to by-pass the obstruction in the aorta is present early in fetal life, and the baby at birth is well supplied with collateral channels. When the ductus closes, there is no change in the dynamics of the circulation. These infants usually have no difficulty and survive to adult life. There is little or no evidence of left ventricular strain in early life, and usually there are no symptoms until adolescence or later.

If the coarctation is proximal to the ductus (infantile type) and the ductus is patent, the diagnosis can be made in infants, because desaturated blood flows to the lower part of the body and cyanosis is present in that area. If the ductus closes, femoral-artery pulsations diminish and the systolic pressure in the legs decreases; in addition, symptoms and signs of left ventricular failure may develop. By the prompt administration of digitalis and oxygen the infant may survive until collateral circulation develops. However, left ventricular failure with pulmonary congestion may result in death of the infant before this occurs. By surgical intervention the infant's life may be saved.

The diagnosis of coarctation of the aorta which is distal to the ductus (adult type) may be made shortly after birth by noting the absence of pulsation in the femoral arteries. There usually are no symptoms, the size of the heart may be normal, and the electrocardiogram may remain normal if the collateral vessels are well developed. During childhood or early adolescence, symptoms secondary to the high blood pressure in the cerebral circulation and low pressure in the lower extremities may become apparent. These consist of headache and claudication after exercise. Roentgenograms often show notching of the lower borders of the ribs as the result of tortuosity and high pressure in the intercostal collateral vessels. Electrocardiograms frequently show evidence of left ventricular preponderance of greater magnitude than is usual for a child, or frank left ventricular hypertrophy. Blood pressure is increased in the arms and decreased in the legs.

Although the diagnosis is seldom in doubt, special procedures are available to confirm the clinical impression. Direct measurement of the pressure in the radial and femoral arteries reveals the pressure difference and

demonstrates the delay in onset of the femoral pulse as compared with the radial. Retrograde aortography may be used to show the coarctation and outline its size and length, thus aiding the surgeon in planning the operation.

Aortic and Subaortic Stenosis

Congenital stenosis of the aortic valve is an uncommon anomaly. The defect usually consists in a fusion of the leaflets of this valve, producing a small, central opening. Because the obstruction to the flow of blood from the left ventricle into the aorta may be great, left ventricular hypertrophy and failure may occur in early infancy. The proper diagnosis has usually not been made during life in the cases reported, but proper evaluation of the symptoms and signs should enable the physician to suspect this condition. The symptoms of left ventricular failure do not differ from those observed in the other anomalies described. A harsh, systolic murmur in the aortic area associated with left ventricular enlargement, as demonstrated by roentgenogram and electrocardiogram, in an infant should be sufficient cause for entertaining the diagnosis of stenosis of the aortic valve. Analysis of the type of pulse in a peripheral artery should confirm the clinical impression. Surgical correction of the stenosis is theoretically possible.

Subaortic stenosis is considerably more common than aortic valvular stenosis. This lesion consists in obstruction of the outflow tract of the left ventricle in the presence of a normal valve. The narrowing is usually of small degree and produces no symptoms in infants and children. Subaortic stenosis can be detected by the existence of a harsh, systolic murmur in the aortic area with extension into the vessels of the neck, a normal aortic second sound and no evidence of aortic regurgitation. The heart usually is of normal size, and the electrocardiogram shows no abnormalities or slight left ventricular hypertrophy.

Endocardial Sclerosis, Anomalous Origin of the Left Coronary Artery from the Pulmonary Artery, and Glycogen Storage Disease of the Heart

These conditions are similar in their manifestations in infants and are grouped together for this discussion. Endocardial sclerosis is far more common than the other two diseases.

Endocardial sclerosis is considered to be a congenital abnormality, although the cause of the condition is not known and an inflammatory basis is not completely excluded. Within recent years a large number of cases of this condition have been reported in medical literature. The lesion is a fibrotic thickening of the endocardial tissue of the left ventricle with occasional involvement of the left atrium and rare involvement of the right ventricle and atrium. The fibrosis results in splinting of the left

ventricle with restriction of diastolic filling of that chamber and eventual decompensation.

Symptoms of endocardial sclerosis are those that occur with failure of the left ventricle. The clinical course may be short, lasting only a few days from the onset of symptoms, or prolonged, with symptoms present for several weeks or months. The typical history of a baby with endocardial sclerosis indicates normal development for several months after birth

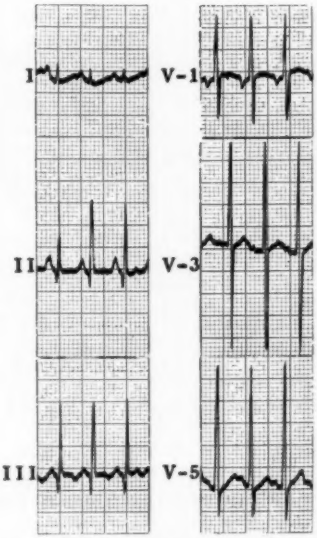

Fig. 47. Electrocardiogram of a 4 month old girl with endocardial sclerosis. Development had been normal to the age of 3½ months, when loss of appetite, rapid respiration and irritability occurred. Examination showed a rapid heart rate, no murmurs, dyspnea and cyanosis. The heart was large according to roentgenographic evidence. The electrocardiogram shows left ventricular hypertrophy with prominent S wave in V_1 and tall R wave in V_5. The infant died, and necropsy disclosed endocardial sclerosis.

followed by a sudden or gradual onset of irritability, loss of appetite, rapid respiration and dyspnea. Physical findings include evidence of dyspnea, cardiac enlargement, tachycardia, no cardiac murmurs or a soft systolic murmur over the precordium, pulmonary congestion and, frequently, enlargement of the liver. Roentgenographic examination shows cardiac enlargement with pulmonary congestion. Evidence of hypertrophy of the left ventricle is usually demonstrated by electrocardiogram (Fig. 47). Pulsation of the femoral arteries is normal.

A tentative diagnosis of endocardial sclerosis can be made if all the symptoms and signs described are present. Final proof may be lacking unless the heart can be examined pathologically. Differential diagnosis

includes anomalous origin of the left coronary artery from the pulmonary artery, glycogen storage disease of the heart, and isolated myocarditis.

Anomalous left coronary artery is an uncommon condition. The symptons may be much the same as with endocardial sclerosis, though there may be more distress after eating or crying and the electrocardiogram may show evidence of myocardial ischemia with inversion of the T waves over the left ventricle, especially immediately after feedings, rather than the pattern of left ventricular hypertrophy.

Glycogen storage disease of the cardiac type is extremely uncommon, and few cases have been reported. Symptoms may be the same as those in endocardial sclerosis, and cardiac enlargement occurs. There are few examples of complete electrocardiographic study of these cases, but it might be expected that the pattern of left ventricular hypertrophy would not be so prominent, since the thickness of the heart muscle is partially the result of deposits of glycogen rather than pure hypertrophy of the muscle.

Isolated *myocarditis* may follow an acute disease, or it may occur without any definite preceding illness. Symptoms and signs may be almost identical with those of endocardial sclerosis, and only pathologic examination can positively differentiate the two diseases. Infants with myocarditis frequently recover completely without evidence of residual cardiac damage, and such a course would constitute strong evidence for such a diagnosis, since recovery from endocardial sclerosis probably does not occur or is extremely uncommon.

GROUP 2. CONDITIONS CAUSING INCREASED RIGHT VENTRICULAR WORK

There are several types of congenital heart disease unaccompanied by cyanosis in which the anomaly results in increased flow or obstruction to the flow of blood through the right side of the heart with increased work for the right ventricle and eventual right ventricular failure. Atrial septal defect, anomalous drainage of some of the pulmonary veins into the right atrium, and defect in the muscular part of the ventricular septum result in an increase in volume of blood flow through the right ventricle. Stenosis of the pulmonary valve with intact atrial and ventricular septa, and pulmonary hypertension secondary to patent ductus arteriosus or defect in the membranous part of the ventricular septum result in an increase in the pressure in the right ventricle because of obstruction to the flow of blood.

Atrial Septal Defect

Atrial septal defect is one of the most common congenital cardiac anomalies. The anatomic defect may consist of an open foramen ovale

in which the valve is not competent or an actual defect in the septum. In either case the result is free communication between the right and left atria. Though the pressure in the right atrium may equal, or be greater than, the pressure in the left atrium at the time of birth and shortly thereafter, later the pressure in the left atrium exceeds that in the right and flow of blood is from left to right. Since left atrial blood is fully saturated with oxygen, there is no cyanosis. The result is an increase in volume of blood in the right atrium, right ventricle and pulmonary system because

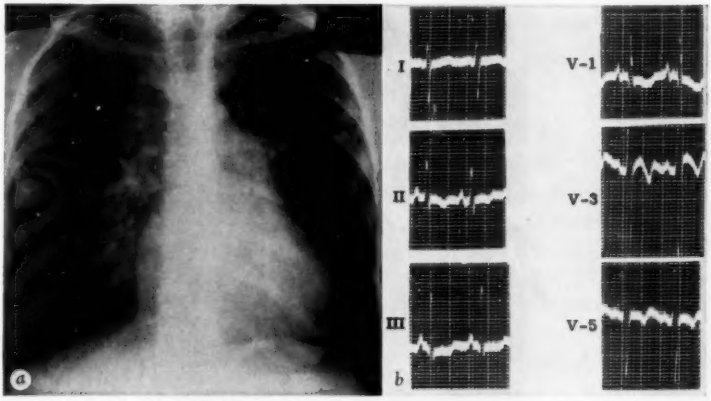

Fig. 48. Roentgenogram and electrocardiogram of an 8 year old girl with atrial septal defect and anomalous drainage of part of the pulmonary veins into the right atrium. The child weighed 43 pounds and had always been small and underweight. A systolic heart murmur was present in the pulmonic area. The roentgenogram, *a*, shows that the heart is enlarged, with a prominent shadow of the pulmonary-artery trunk and increased pulmonary vascular markings. The electrocardiogram, *b*, shows delayed activation of the right ventricle with RSR′ in V_1. Catheterization revealed arterialization in the right atrium with normal pressure in the right ventricle and pulmonary artery.

of recirculation through the lungs. The left ventricle and aorta do not participate in this increased flow. The volume of blood passing through an atrial septal defect may be small or large, depending upon the size of the defect. As much as 70 per cent of the blood entering the left atrium from the lungs may traverse the defect and recirculate. Such a shunt produces dilatation of the right atrium and right ventricle and, presumably, accounts for the characteristic murmur of this condition, because a large amount of blood enters the relatively narrow outflow tract of the right ventricle.

Clinical features of a large atrial septal defect include poor physical development because of deficient systemic circulation, left-sided deformity of the thorax as a result of enlargement of the right ventricle, and a large, overactive heart with a forceful, heaving apical thrust. There is a

blowing, systolic murmur in the pulmonic area with an accentuated, reduplicated second heart sound. A thrill may be present, but usually not in infancy and early childhood.

Radiographic and radioscopic examinations frequently are of great aid in establishing the diagnosis (Fig. 48, *a*). The features are enlargement of the right atrium and right ventricle, prominence of the pulmonary-artery segment and increased pulmonary vascular markings with prominent pulsations.

Electrocardiographically, the incomplete right-bundle-branch-block type of pattern is frequently present, suggesting dilatation as well as

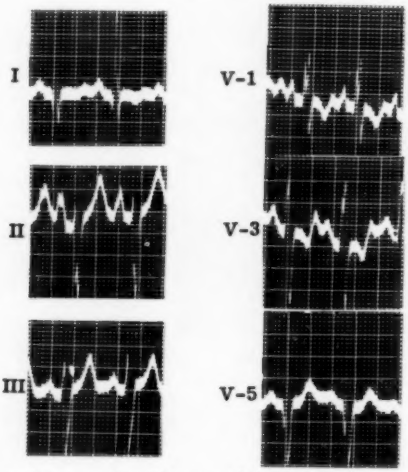

Fig. 49. Electrocardiogram of a 2½ year old girl with atrial septal defect. This child was underweight and seemed to tire with moderate activity. The heart was large and overactive, with a loud systolic murmur in the pulmonic area. The second pulmonic sound was loud and reduplicated. There were prominent pulmonary vascular markings. The electrocardiogram shows the complete right-bundle-branch-block type of pattern often seen in atrial septal defect. Catheter studies showed arterialization in the right atrium without increased right ventricular pressure.

hypertrophy of the right ventricle (Fig. 48, *b*). Exaggerated P waves are also common. No evidence of left ventricular hypertrophy is seen. Right bundle branch block may be complete (Fig. 49).

A small defect in the atrial septum may produce no symptoms and cause little or no enlargement of the heart. The flow of shunted blood may be relatively small, and there may be only a soft, blowing systolic murmur in the pulmonic area. Pulmonary vascular shadows may be only slightly increased, and the electrocardiogram may be normal or show only a slight delay in depolarization of the right ventricle in precordial leads from the right side of the thorax.

Cardiac catheterization is the most valuable special diagnostic procedure in cases of atrial septal defect. Arterialization of blood in the right atrium can be demonstrated and the amount of shunted blood can be calculated. Occasionally it is possible to pass the catheter through the defect into the left atrium. Catheter studies are also of value in determining whether or not there is an increase in pressure in the right ventricle and the pulmonary artery, since some patients have this complication relatively early in childhood, and such a finding may affect the decision regarding surgical closure of the atrial septal defect.

Partial Anomalous Pulmonary Venous Drainage

One or more of the pulmonary veins may enter the right atrium or one of the great, systemic veins leading into the right atrium. The most common situation consists of one or two pulmonary veins draining a portion of the right lung, rarely a portion of the left lung, and entering the right atrium directly. All the pulmonary veins may enter the right atrium with mixing of systemic venous and pulmonary oxygenated blood, but this condition should be classed with cyanotic types of congenital heart disease. Functionally anomalous pulmonary venous drainage may occur with the pulmonary veins entering the left atrium near an atrial septal defect and discharging blood directly into the right atrium. The latter situation is probably relatively common, but anatomic anomalous pulmonary venous connection is uncommon.

The abnormality under discussion produces clinical, roentgenographic and electrocardiographic changes similar to, though less extensive than, those that may occur in atrial septal defect. Differentiation must sometimes be made by means of cardiac catheterization and analysis of dilution of dye injected into the right and left pulmonary arteries and into the right atrium and venae cavae. The importance of differentiation of anomalous pulmonary venous drainage from atrial septal defect is apparent if surgical treatment is contemplated.

Defect in the Muscular Portion of the Ventricular Septum

Ventricular septal defect low in the septal wall results in a shunt of blood from the left ventricle into the right ventricle, increasing the work of both ventricles, since both participate in the propulsion of the increased volume. The clinical picture is identical with that of high ventricular septal defect, except that there is early evidence of right ventricular hypertrophy as well as left, and the electrocardiogram often reflects this situation.

Stenosis of the Pulmonary Valve

Stenosis of the pulmonary valve without ventricular or atrial septal defect is a relatively common congenital malformation, ranking just behind patent ductus, atrial septal defect and ventricular septal defect in frequency. The anomaly consists of an abnormal pulmonary valve in which the leaflets of the valve are partially fused, leaving a small, central orifice which constitutes an obstruction to the flow of blood from the right ventricle to the pulmonary artery. There may be some narrowing of the outflow tract of the right ventricle because of hypertrophy of the muscle, in addition to stenosis of the valve. Since the atrial and ventricular septa are intact, there is no mixing of blood between the right and left sides of the heart, and no cyanosis occurs. Frequently, stenosis of the pulmonary valve is associated with atrial septal defect or open foramen ovale, resulting in right-to-left flow and cyanosis.

The diagnosis of stenosis of the pulmonary valve is sometimes difficult in infants, but can usually be made with confidence in children beyond the age of three or four years. Because of obstruction of the flow of blood from the right ventricle, hypertrophy of the right ventricular muscle results. A major symptom is intolerance of exercise, consisting in "loss of wind" and puffing with running. Physical examination reveals a heart that is usually not overactive or heaving and not greatly enlarged. There is a systolic thrill and a harsh, systolic murmur in the pulmonic area with extension toward the left clavicle, but fading toward the apex. The second heart sound at the pulmonic area is characteristically single and not accentuated.

Roentgenograms of the thorax may show slight or moderate cardiac enlargement, prominence of the pulmonary-artery segment as the result of poststenotic dilatation, and normal pulmonary vascular markings (Fig. 50, *a*). The last-mentioned finding is not generally recognized. Since all the blood entering the right side of the heart must enter the pulmonary system, the flow of blood to the lungs is not diminished in volume, although the pressure may be low. This is in contrast to the situation found in the tetralogy of Fallot and pulmonic stenosis with atrial septal defect, which allow a shunt of blood from right to left and result in diminished volume of pulmonary flow. Roentgenoscopic examination shows no pulsations in the peripheral pulmonary arteries, although the pulmonary trunk may pulsate because of the jet of blood entering it through the small opening in the valve.

Electrocardiographic characteristics of stenosis of the pulmonary valve are evidence of a thick-walled right ventricle and, frequently, exaggerated, peaked P waves suggesting right atrial enlargement (Fig. 50, *b*).

The degree of stenosis of the pulmonary valve is variable. If the opening is very small, there is early right ventricular hypertension and strain.

If the opening is larger, the right ventricle may compensate satisfactorily and the patient may live a relatively normal life. In this condition cardiac catheterization is most important to detect the degree of right ventricular hypertension and to select the cases suitable for pulmonary valvulotomy.

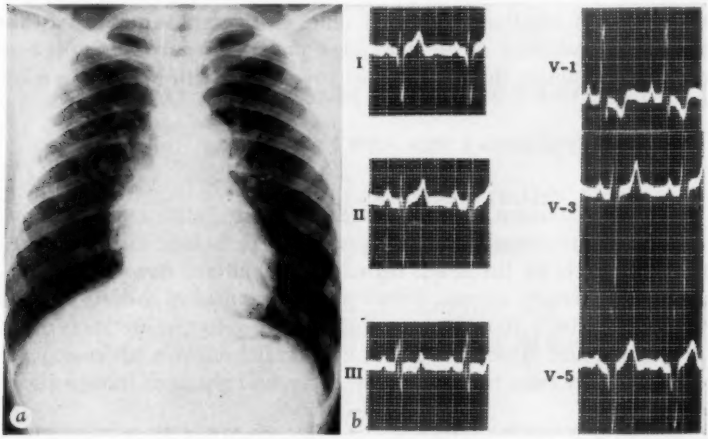

Fig. 50. Roentgenogram and electrocardiogram of a 14 year old boy with stenosis of the pulmonic valve. A murmur had been present since infancy. The boy was active and had no symptoms. A systolic thrill and murmur were present in the pulmonic area. The second pulmonic sound was single and not loud. The roentgenogram, *a*, shows slight enlargement of the heart with prominent pulmonary-artery segment and normal pulmonary vascular markings. The electrocardiogram, *b*, discloses right ventricular hypertrophy with a tall R wave in V_1 and delayed intrinsicoid deflection. Catheterization demonstrated a right ventricular pressure of 110 to 120 mm. of mercury systolic and a pulmonary-artery pressure of 25/6. There was no evidence of septal defects. Pulmonary valvulotomy was performed.

Pulmonary Hypertension Secondary to Increased Pulmonary Flow

This category includes all the conditions associated with an increased flow of blood through the pulmonary system, including atrial septal defect, patent ductus, ventricular septal defect and anomalous pulmonary venous drainage. There are no serial catheter studies of individual patients with increased pulmonary flow over a span of many years that provide data regarding pressure in the pulmonary artery. Some young children have been found to have pulmonary hypertension in association with one of the shunts mentioned. On the other hand, some adults have no pulmonary hypertension after having had a tremendous pulmonary flow for years. The clinical course of patients who have gradually developing pulmonary hypertension has been observed many times with evidence of increasing pressure in the pulmonary artery and eventual reversal of the flow of blood through the defect and the development of

cyanosis. This is evidence in support of the theory that increased flow may lead to increased pressure. When this complication occurs, the primary picture of the congenital anomaly changes. Evidence of hypertrophy of the right ventricle appears roentgenologically and electrocardiographically, and the left-to-right shunt of blood may be reversed to a right-to-left shunt with resultant cyanosis. Failure of the right ventricle may also ensue. This evolution of the pathologic physiology must be understood in order to evaluate the condition of any patient with cyanosis as a late manifestation.

SUMMARY

The more common types of congenital heart disease unaccompanied by cyanosis are described in relation to the pathologic physiology and resultant effects on the heart. Because of the altered flow of blood and changes in pressure, increased work may be required of the left ventricle in patent ductus arteriosus, ventricular septal defect, coarctation of the aorta, aortic and subaortic stenosis, endocardial sclerosis, anomalous left coronary artery from the pulmonary artery, and glycogen storage disease of the heart.

Those conditions resulting in increased work for the right ventricle include atrial septal defect, partial anomalous pulmonary venous drainage, defect low in the ventricular septum, stenosis of the pulmonary valve, and pulmonary hypertension secondary to increased flow of blood through the pulmonary system.

Symptoms, physical signs and roentgenologic and electrocardiographic features for each condition are mentioned, and a few examples are described. The value of cardiac catheterization or retrograde aortography in some of the conditions is pointed out.

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CLINICAL DIAGNOSIS OF THE CYANOTIC TYPES OF CONGENITAL MALFORMATIONS OF THE HEART

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In the discussion of the diagnosis and the differential diagnosis of the various types of congenital cyanotic heart malformations, we have decided not to approach it from the classical aspect of considering individual entities and syndromes. Since patients present themselves, not as examples of a particular entity, but as problems in the differential diagnosis of the entire group of congenital malformations of the heart, we decided to consider first the differential diagnosis of the presenting symptoms and signs and later to point out the outstanding clinical findings of each entity and syndrome.

We have found it most convenient to approach this problem through the following considerations: (1) Is the patient actually cyanotic, and is the cyanosis of cardiac origin? (2) Does the physical examination reveal cardiac enlargement, and what is the significance of the murmurs heard? (3) Do the fluoroscopic and roentgenographic examinations reveal normal, increased or decreased vascular markings, and which cardiac chambers are enlarged? (4) Does the electrocardiogram reveal right or left atrial and ventricular hypertrophy and strain or combined hypertrophy and/or strain?

The experience of others and our own observations have led us to believe that in the overwhelming majority of cases the decision as to whether a particular patient can be benefited by surgical intervention can be made by correlating the history, physical examination, fluoro-

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scopic, roentgen ray and electrocardiographic findings. This correlation may not lead to an exact diagnosis, and in our own practice we obtain invaluable aid from studies such as angiocardiography and cardiac catheterization. We would indeed be unhappy if these techniques were not available to us, because our presently held clinical concepts are at least in part due to the information obtained from these studies. At present, however, though in exceptional cases they may even change the clinician's decision as to the advisability of operative intervention, they are for the most part simply of value as confirmatory evidence of the clinical diagnosis.

These tests must never be considered a substitute for a thorough history and examination. If they are used in lieu of clinical evaluation, they may do much more harm than good.

I. IS THE PATIENT ACTUALLY CYANOTIC, AND IS THE CYANOSIS OF CARDIAC ORIGIN?

The child or infant who manifests marked cyanosis and the attendant clubbing of the fingers and nails is easily recognized and is usually brought in by the parents as a "blue baby." There is, however, a large group that shows only a subclinical cyanosis which even the experienced clinician may find difficult to recognize.

By way of explanation of this statement we must remember that the normal oxygen saturation is from 95 to 97 per cent. In the presence of a normal red blood cell count and hemoglobin, clinical cyanosis will not become apparent until oxygen saturation has dropped to a level of 70 to 75 per cent. The cyanosis then depends, not upon the saturation, but upon the actual amount of reduced hemoglobin in the circulating blood. This amount represents roughly 5 gm. or more per 100 cc. of blood.

Therefore if anemia is marked, as it may occasionally be in young infants, the oxygen saturation may be even less than 70 per cent and no cyanosis be visible, since the total amount of reduced hemoglobin is less than 5 gm. per 100 cc. Conversely, in the presence of polycythemia the cyanosis may be visible with saturation as high as 85 per cent or higher, because the total amount of hemoglobin and consequently the total amount of reduced hemoglobin is increased to over the 5 gm. level.

Since children with a normal red blood count will not show cyanosis if the saturation is over 75 per cent, even when the arterial blood is unsaturated as shown by oximetry or Van Slyke determinations, we often have difficulty in stating definitely that a child is in the cyanotic group. If, in addition, the child has a heavily pigmented skin, this difficulty is increased.

In case of doubt, observe the child during and after an episode of crying or after exercise; a latent cyanosis may then become much more

obvious. This examination must be made in good natural light (artificial light has led us into several errors in the diagnosis). If the cyanosis is still questionable, occasionally an increase in the hemoglobin and red blood count will indicate an underlying cyanosis.

Arterial blood is difficult to obtain in young infants, and we have therefore made it routine practice to use the ear oximeter to determine the saturation. Though this procedure is not as accurate as the Van Slyke determination, it is painless and simple and of great help to the clinician.

Having determined that the patient is cyanotic, we must then decide whether the cyanosis is on a cardiac basis. The differentiation from congenital or acquired methemoglobinemia, polycythemia vera, chronic or extensive pulmonary disease, diaphragmatic hernia or involvement of the central nervous system in the newborn can usually be easily established.

The idea that cyanosis, if due to congenital malformation of the heart, must be present at birth is an erroneous one. Some infants with a cyanotic type of congenital malformation of the heart may not be cyanotic for the first few weeks or months of life because of the patency of the ductus arteriosus, which serves as a physiologic Blalock or Potts-Smith-Gibson operation.

In congenital or acquired methemoglobinemias the cyanosis has a grayish tint and is universally distributed over the whole body. Spectroscopic examination will quickly differentiate this condition. Polycythemia vera shows an increase in the hemoglobin and of the red cell count, but the oxygen saturation is usually normal, and there is usually no clubbing of the fingers or toes.

The presence of extensive lung or diaphragmatic acquired or congenital abnormalities will usually be manifested by physical examination. A helpful clinical sign is the decrease in the cyanosis upon crying, which is the opposite of the result in the cardiac patient. Oxygen administration will also decrease the cyanosis considerably and has much less effect in the cardiac malformation.

The cyanosis in the newborn which is related to central nervous system damage is usually intermittent, and other signs of nervous system involvement are usually present, such as absence of the Moro and sucking reflexes, the presence of the cephalic cry and rigidity or flaccidity of extremities.

One other feature of cyanosis deserves mention at this point. We had been impressed with the finding of marked cyanosis in the hands and much less cyanosis in the feet in cases of transposition of the great vessels with coarctation or atresia of the aortic isthmus and therefore routinely examined the hands and feet after they had been placed together and next to each other. We believe, however, that this sign has been overemphasized in the literature. In our experience, such cyanotic types of congenital malformation of the heart as tetralogy of Fallot, tricuspid atresia and

others may show considerably less cyanosis in the toes than in the fingers. We are unable to explain this phenomenon except for the possibility of greater vascularization and dilatation of the capillaries of the hands than of the feet. That this is not a true difference we have now demonstrated to our own satisfaction by simultaneous femoral and brachial artery oxygen determinations which were shown to be identical. We have therefore found this sign at times to be confusing, and have come to depend upon the actual oxygen saturations of the brachial and femoral arterial blood.

II. DOES THE PHYSICAL EXAMINATION REVEAL CARDIAC ENLARGEMENT, AND WHAT IS THE SIGNIFICANCE OF THE MURMURS HEARD?

It is usually possible by inspection, palpation and percussion to determine the site of the apex beat and whether the region of the pulmonary artery (second left interspace) is widened. Occasionally, however, an actual enlargement cannot be made out by this method. Right ventricular hypertrophy may be suggested by a bulge of the anterior chest wall and a diffuse cardiac impulse over the lower precordium. A heaving apical impulse which is displaced outward and downward is usually indicative of left ventricular hypertrophy. The simplest and still the best method of differentiating dextrocardia with situs inversus from dextroversion or a normal position of the heart is the palpation of the apex beat and the relation of this to the position of the liver.

In auscultation, particular attention is directed to the location, the point of maximal intensity, the character, the transmission and the timing of the murmur. The age at which the murmur first appears is also of great importance. Some cases of congenital heart disease never manifest a murmur, such as those of transposition of the great vessels or tetralogy of Fallot with complete atresia of the pulmonary artery, even though cyanosis in these cases is severe and early in onset.

A common trunk, on the other hand, may give rise to a continuous systolic and diastolic murmur heard either over the pulmonic or aortic areas or over the lung fields. In general, however, the murmur is not of as much help in the differentiation of the cyanotic type of congenital heart disease as it is in the noncyanotic group.

Auscultation is, however, of great importance in the determination of the quality and character of the second pulmonic sound. It must in each individual case be compared to the second aortic sound in the same patient. A marked accentuation of the second pulmonic sound more than that expected in the normally louder second pulmonic sound in infants and children is indicative of an increased pressure in the pulmonary circulation. It may be helpful in ruling out pulmonary stenosis or a decreased pulmonary blood flow.

When the second pulmonic sound is markedly reduced in comparison to the second aortic sound or is absent, it is diagnostic of a decreased pulmonary artery pressure and a decreased pulmonary blood flow.

However, in cases of transposition or of marked dextroposition of the aorta the aorta lies anteriorly and may actually give its maximal sound in the pulmonary area. A split second pulmonic sound would rule out a common trunk.

Thrills palpable over the precordium have much the same significance as the murmurs and add little, except that we have noted on occasion that an isolated pulmonic stenosis will give much the same suprasternal thrill that has been noted and described in aortic and subaortic stenosis.

III. DO THE FLUOROSCOPIC AND ROENTGENOGRAPHIC EXAMINATIONS REVEAL NORMAL, INCREASED OR DECREASED VASCULAR MARKINGS, AND WHICH CARDIAC CHAMBERS ARE ENLARGED?

Examination by fluoroscopy or on roentgen ray film is of the utmost help in the classification and differentiation of cyanotic heart disease into operable and inoperable cases. Fluoroscopy is usually to be preferred to roentgenography, for while the vessels may show up better on film, it is difficult to distinguish them from increased bronchial markings. The fluoroscope, though it does not give as good a definition of the structures, allows the visualization of the pulsations in the vessels and thus their differentiation from the bronchial markings.

A division can then be made after a careful fluoroscopic and roentgen ray examination between those with increased pulmonary blood flow and those with decreased flow.

In addition to the evaluation of the pulmonary blood flow, the fluoroscopic and roentgen ray examination is of much aid in the evaluation of chamber enlargement.

Though it is not in the province of this article to discuss fully the fluoroscopic and roentgenologic findings of the normal and abnormal heart, we wish to emphasize the points we have found to be of the utmost importance in deciding chamber enlargements. We feel strongly that the establishment of the presence or absence of chamber enlargements is essential in the differential diagnosis of congenital malformation of the heart.

Right Ventricular Hypertrophy

The posteroanterior view usually reveals an elevated apex with or without increase in the transverse diameter of the heart. The pulmonary artery segment may be concave if there is hypoplasia or atresia of the artery, or convex if there is dilatation of the artery.

The left anterior oblique view usually reveals a convexity of the anterior cardiac border, with or without widening of the diaphragmatic surface of the right ventricle. In other words, the right ventricle may be enlarged even though it does not approach the anterior chest wall as long as the anterior cardiac border is convex.

The right anterior oblique view may reveal the pulmonary artery to be concave in patients with infundibular stenosis, such as tetralogy of Fallot or absent right outflow tract such as truncus communis. In other malformations it is straight or convex. The area just below may bulge anteriorly.

Left Ventricular Hypertrophy

The posteroanterior view may show an increased convexity of the left border or an elongation of that border downward and laterally. The pulmonary artery segment is usually concave, but may be straight or convex if there is a concomitant dilatation of the pulmonary artery.

In the left anterior oblique view the amount of rotation necessary to clear the posterior surface of the left ventricle from the spine varies considerably, being less in the vertical than in the horizontal heart. A degree of rotation in excess of the usually expressed normal value of 55 degrees does not, in our experience, necessarily indicate left ventricular hypertrophy. A markedly hypertrophied right ventricle may push the left ventricle posteriorly and give the false impression of left ventricular hypertrophy.

The only positive evidence in this view, which unfortunately is rarely visualized, is the downward and forward displacement of the interventricular groove.

The right anterior oblique view may reveal a bulge of the lower anterior segment. This, however, may be due to right ventricular hypertrophy as well as left.

Right Auricular Enlargement

The posteroanterior view usually reveals increased convexity of the right border of the heart below the superior vena cava.

The left anterior oblique view may reveal a more horizontal position of the appendage of the right auricle, as shown by an increased distance between the anterior ventricular border of the right ventricle and the ascending aorta. Unless this line is horizontal this sign is not very useful, because exact normal values in infants and children have not been established.

In the right anterior oblique view only marked enlargement of the right auricle will be shown by opacification of the lowermost portion of the retrocardiac space.

Left Auricular Enlargement

The posteroanterior view may reveal a double contour of the right cardiac border or a convexity just below the pulmonary artery segment on the left border. This occurs only in marked left auricular enlargements. The left bronchus may be elevated.

The right anterior oblique view usually reveals the barium-filled esophagus to be displaced posteriorly in the midretrocardiac space. This posterior displacement must be distinguished from that normally occurring if the roentgenogram is taken during expiration, especially in infants.

The left anterior oblique view may reveal elevation and compression of the left bronchus and also a posterior compression of the barium esophagram in the region of the left auricle.

Since cyanotic types of congenital malformations of the heart may have a right aortic arch, the following points will bring this out.

The posteroanterior view of the conventional roentgenogram may show the aortic knob on the right side. The barium esophagram will show a displacement of the esophagus to the left in the posteroanterior view, and posterior displacement in the left anterior oblique view.

IV. DOES THE ELECTROCARDIOGRAM REVEAL RIGHT OR LEFT ATRIAL AND VENTRICULAR HYPERTROPHY AND STRAIN OR COMBINED HYPERTROPHY AND/OR STRAIN?

The electrocardiogram by itself can establish the diagnosis of three congenital entities: dextrocardia, Wolff-Parkinson-White syndrome, and complete heart block. The latter may or may not be on a congenital basis. The presence or absence of the various arrythmias and conduction disturbances is of little help in the differential diagnosis of congenital malformations of the heart. The electrocardiogram, however, is of great help in bringing out right or left ventricular or auricular hypertrophies or of combined hypertrophies. In our experience the decision as to the presence of chamber enlargements can often be made by a study of the fifteen lead electrocardiogram, and we believe that the electrocardiogram is often of greater value than roentgenology and fluoroscopy. Because the heart may be of the vertical or horizontal type and because there may be clockwise or counterclockwise rotation of the heart along its long axis or forward or backward rotation of the apex, the standard leads cannot be used to determine ventricular hypertrophies. We routinely take fifteen leads, which include the three standard leads, aV_R, aV_L, aV_F, V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_{3R} and V_{4R}. We wish to bring out only the salient points in the differential electrocardiographic diagnosis of various cardiac hypertrophies.

Left ventricular hypertrophy and/or strain may show the following:

1. qR in aV_L with the R more than 13 mm. high and the sum of R in

lead I and of S in lead III more than 25 mm. high, or the sum of S in V_1 and R in V_6 more than 40 mm. high.

2. In addition to these findings, a depression of the S-T segments with inversion of the T waves in leads I, aV_L, V_5, V_6, and V_7 aids in the diagnosis of left ventricular hypertrophy. These findings occur if the electrical position of the heart is horizontal. If the position is vertical, then the qR will appear in aV_F and the R will be more than 20 mm. high and the sum of R in leads II and III will be over 40 mm. high. The depression of the S-T segments may then occur in leads II and III instead of I. Lead aV_R may show an rS with an elevated S-T segment and an upward T wave.

   The intrinsicoid deflection of the R in leads over the left ventricle, and in V_5 and V_6 may be prolonged over 0.045 second.

Right ventricular hypertrophy may be diagnosed in children over the age of approximately one year by the presence of a tall R over the epicardial surface of the right ventricle, such as V_1, V_2, V_{3R} and V_{4R} with either no S wave or R which is at least three or four times as tall as s, and deep S over the epicardial surfaces of the left ventricle, such as V_5, V_6. This may occur normally in infants. In infants as well as in children the presence of qR in V_1, V_2 or V_3 and the intrinsicoid deflection over V_1, V_2 longer than over V_5 or V_6 are direct signs of right ventricular hypertrophy. The R/S ratios over the epicardial surfaces of the ventricles normally differ so much through a wide range that exact rules are inadvisable.

Normally T waves may be inverted in infants and children in V_1, V_2, V_3 and V_4. During the first few days of an infant's life the T waves may be inverted over V_5, V_6 and upward over V_1, V_2, V_3 and V_4. Tall peaked P waves over 2.5 mm. on leads II, III, V_1 and V_2 are a sign of right auricular hypertrophy and may occur in combination with either right or left ventricular hypertrophy. Widening and notching of the P wave, especially in lead I, is usually indicative of left auricular hypertrophy and may also occur in either right or left ventricular hypertrophy.

GROUP I. CLINICAL ENTITIES WITH DECREASED PULMONARY BLOOD FLOW

Tetralogy of Fallot

Clinical Findings. Cyanosis is usually not apparent until several months of age because of the early patency of the ductus arteriosus. In extreme cases cyanosis is present at birth. There is increasing dyspnea. Squatting is common. Clubbing of the fingers and toes appears some months after the onset of cyanosis. Attacks of unconsciousness may occur. The heart is usually not enlarged. A systolic thrill and murmur are usually present over the second, third and fourth left interspaces, but in exceptional cases

may be absent. The second pulmonic sound is usually diminished, but may appear normal because of the dextroposition of the aorta.

Fluoroscopy and Roentgenography. The transverse diameter of the heart is not noticeably enlarged. The apex is usually elevated. The pulmonary artery segment is usually concave, but may be straight or convex if there is poststenotic dilatation. The pulmonary vascular pulsations are decreased. The left anterior oblique view reveals a hypertrophy of the right ventricle and a clear and wide aortic window if there is marked pulmonary stenosis. A right aortic arch is present in about 20 per cent of cases.*

Catheterization. High pressure in the right ventricle usually approximates the systemic pressure. There is low pressure in the pulmonary artery distal to the stenosis. A decreasing gradient may be present in infundibular stenosis between the right ventricle and the pulmonary artery. There is diminished pulmonary blood flow. The oxygen saturation of the right ventricular blood may be higher than that of the right auricle. Peripheral arterial oxygen saturation is lowered in varying degrees, depending upon the right-to-left shunt.

Tricuspic Atresia or Stenosis

Clinical Findings. These are similar to those in the tetralogy of Fallot, except that they are usually more severe and earlier in onset. Right heart failure as evidenced by venous engorgement and enlarged liver may appear early.

Fluoroscopy and Roentgenography. The heart is usually not enlarged. Occasionally marked right auricular enlargement may be seen in the posteroanterior view, giving the heart a false appearance of a dextrocardia. The lung fields are clear. There is a concavity in the pulmonary artery segment. The anterior oblique view reveals a "shaved-off" appearance of the right ventricle and a clear aortic window.

Catheterization. The catheter enters the left auricle, and the left ventricle from the right auricle. There is a shunt from right to left with diminished peripheral arterial oxygen saturation. In case of stenosis instead of atresia, the catheter may enter the right ventricle and pulmonary artery. The pressures in these chambers will be low.

Pulmonary Stenosis with Interauricular Communication

Clinical Findings. Cyanosis usually appears late and is of mild degree. We have, however, seen a number of infants born cyanotic and with early right heart failure because of a marked valvular stenosis. Dyspnea

* Angiocardiographic findings are presented in the paper by Dr. John D. Keith in this volume.

may be prominent and is out of proportion to the degree of cyanosis. There is a systolic thrill and a harsh, loud murmur over the pulmonary area. The second pulmonic sound is absent or diminished. If the stenosis is severe, there is a gradual, progressive enlargement of the heart.

Fluoroscopy and Roentgenography. There may be marked enlargement of the transverse diameter of the heart, especially in infants with severe stenosis. The apex is elevated. The pulmonary artery segment is convex. Pulmonary vascular markings are normal to decreased. The left anterior oblique view may show marked right ventricular hypertrophy.

Angiocardiography. The right oblique or lateral view is best to visualize the valvular stenosis and the poststenotic pulmonary dilatation. The left auricle may be seen early as dye enters it from the right auricle. If this happens, the left ventricle and the aorta may be visualized early, possibly causing confusion with a tetralogy of Fallot. Dye persists in the pulmonary artery for many seconds.

Catheterization. The pressure in the right ventricle may be much higher than that in the systemic circulation. There is low pressure past the stenosis in the pulmonary artery. Peripheral arterial oxygen saturation is diminished, thus establishing the diagnosis of a right-to-left shunt.

Pseudotruncus Communis

Clinical Findings. These are similar to those in severe tetralogy of Fallot. The second sound is not duplicated.

Fluoroscopy and Roentgenography. There is no characteristic finding that will differentiate this from severe tetralogy of Fallot.

Angiocardiography. A single wide vessel is seen emerging from the right ventricle. The main pulmonary artery is not visualized.

Catheterization. The catheter enters the single vessel. It cannot enter the pulmonary artery. Since this happens in severe tetralogy of Fallot, catheterization cannot definitely differentiate these entities.

Ebstein's Disease with Interauricular Communication (Cyanotic Type)

Clinical Findings. Marked cyanosis was present soon after birth in 2 patients whom we observed with autopsy findings. The heart was markedly enlarged. Murmurs are not characteristic.

Fluoroscopy and Roentgenography. Marked enlargement of the heart was present in our cases. There was also marked right auricular enlargement. Pulmonary vascular markings were diminished. It was difficult to decide which ventricles were hypertrophied.

Catheterization. The catheter entered the left auricle and left ventricle from the right auricle. The right ventricle could not be entered. All these

findings were consistent with the diagnosis of tricuspid atresia with pulmonary hypoplasia.

The differentiation seems to rest on the marked enlargement of the heart in Ebstein's disease with interauricular septal defect, which is not found in tricuspid atresia. The presence of intraventricular conduction disturbances in Ebstein's disease may be a helpful point.

Single Ventricle with Hypoplastic Pulmonary Artery

Clinical Findings. These are the same as in severe tetralogy of Fallot.

Fluoroscopy and Roentgenography. The heart usually is not noticeably enlarged. The pulmonary artery segment may be either concave or convex. Pulmonary vascular markings are diminished.

Catheterization. There is a marked increase in arterial oxygen saturation of the ventricle from that of the auricle; it should be over 4 volumes per cent. If both the aorta and the pulmonary artery are entered, the arterial oxygen saturation will be approximately the same in both vessels. It is easier for the catheter to enter the aorta than the pulmonary artery.

GROUP II. CLINICAL ENTITIES WITH INCREASED PULMONARY BLOOD FLOW

Complete Transposition of the Great Vessels

Clinical Findings. Cyanosis usually appears early and is intense. At least a patent foramen ovale or patent ductus arteriosus must be present to maintain life. If there is a large interauricular and/or interventricular septal defect, the cyanosis and dyspnea will be less intense and life will be prolonged beyond the period of infancy and occasionally even into later childhood.

Murmurs are of no importance in the diagnosis. The pulmonic second sound is usually loud.

There is a progressive and rapid cardiac enlargement. If there is, in addition, a coarctation of the aorta or atresia of the aortic arch, the clinical diagnosis can be easily established by noting that the toes are *much* less cyanotic than the fingers. However, unless this difference in cyanosis is marked and consistent, this sign may be misleading.

Fluoroscopy and Roentgenography. The heart appears egg-shaped, with a narrow base. Usually there is a concavity in the pulmonary artery segment. The base of the heart usually widens in the left anterior oblique view. Fluoroscopic examination in our experience usually reveals clear lungs with diminished pulmonary blood flow if there are no large interauricular or interventricular septal defects. On roentgenography, however, these infants reveal a mottled, fluffy appearance of the pulmonary

vascular markings. If the patient lives past infancy, there are usually associated large septal defects present, and fluoroscopy then reveals markedly increased pulmonary vascular pulsations. The heart then is definitely increased in size.

Catheterization. There is high pressure in the right ventricle. The catheter usually passes into the aorta. Shunts may be demonstrated in the auricle or ventricle, but we have not been able to demonstrate a bidirectional shunt through these openings. Catheterization cannot definitely establish the diagnosis.

Truncus Arteriosus Communis

Clinical Findings. Although the peripheral arterial oxygen saturation is always diminished, cyanosis may be minimal. In several patients whom we have studied and who later came to autopsy, cyanosis was not apparent until cardiac failure supervened.

A loud, harsh systolic murmur may be present over the second, third and fourth left interspaces, and a continuous machinery systolic and diastolic murmur may be heard to the right and left of the upper sternum and transmitted downwards over the lung fields. The pulmonic second sound is loud and never split. Cardiac enlargement is present.

Fluoroscopy and Roentgenography. There is an enlargement of the transverse diameter of the heart. The apex is usually elevated. There is usually a concavity in the pulmonary artery area. Pulmonary vascular pulsations are markedly increased, sometimes on only one side, if only one large pulmonary artery is present. The right ventricle is hypertrophied, and in the left anterior oblique view a shelf may be seen extending from the anterior border of the heart towards the vertically coursing common vessel.

Catheterization. The catheter enters the common trunk from the right ventricle, which shows pressure approximately the same as that of the systemic pressure. If one of the pulmonary arteries can be entered from the common vessel, the pressure and oxygen saturation will be approximately the same.

Eisemenger Complex

Clinical Findings. Cyanosis is usually not apparent until later childhood or adolescence. There is usually no dyspnea or squatting.

Except for a widened percussion area over the pulmonary artery segment, the heart is usually not enlarged.

A systolic thrill and murmur over the second, third and fourth left interspaces are usually present. The pulmonic second sound is loud and booming.

Fluoroscopy and Roentgenography. The transverse diameter of the heart is either normal or moderately increased. The apex is elevated. The pulmonary artery segment is straight or convex; occasionally there is a marked bulge in this area. The pulmonary vascular pulsations are markedly increased.

The left anterior oblique view usually shows right ventricular hypertrophy, and the aortic window is opacified by the large pulmonary artery.

Catheterization. There is high pressure in the right ventricle and pulmonary artery which usually does not exceed the peripheral systemic pressure. There is increased pulmonary blood flow. Early the peripheral arterial oxygen saturation is only slightly diminished, because the shunt is predominantly from left to right. Later, as the pulmonary resistance is markedly increased, the shunt may be predominantly from right to left and the peripheral arterial oxygen saturation markedly diminished.

Tricuspid Atresia or Stenosis with Complete Transposition of the Great Vessels

Clinical Findings. The clinical findings are similar to those in complete transposition of the great vessels except that cyanosis is less intense. Murmurs are not of help in the diagnosis. The pulmonic second sound is loud. The heart is markedly enlarged in contrast to the absence of enlargement or enlargement of only the right auricle in tricuspid atresia without transposition of the great vessels. This is of great clinical importance, because a Blalock or Potts operation is not indicated in these cases, whereas it is of help in tricuspid atresia without transposition.

Fluoroscopy and Roentgenography. There is marked enlargement of the transverse diameter of the heart and convexity of the pulmonary area. There is marked pulsation of the pulmonary vessels and left ventricular hypertrophy, an important differential point from complete transposition of the great vessels without tricuspid atresia.

Catheterization. The catheter cannot enter the right ventricle, but enters the left auricle and left ventricle. The catheterization findings should be correlated with other findings to establish the diagnosis.

Taussig-Bing Heart

Clinical Findings. Cyanosis is almost the same as in complete transposition except that it is less intense. There is an increased area of dullness over the left base of the heart. Murmurs are of no importance in the diagnosis. The second pulmonic sound is loud.

Fluoroscopy and Roentgenography. There is enlargement of the transverse diameter of the heart. There is a bulge of the pulmonary artery segment. The pulmonary vascular pulsations are increased. There is enlargement of both ventricles, but more of the right one.

Catheterization. The catheter enters the aorta and may enter the pulmonary artery. The arterial oxygen saturation of the pulmonary artery is much greater than that of the right ventricle. Contrary to the usual case of a complete transposition of the great vessels, the catheter easily enters the pulmonary artery.

Single Ventricle with Normal-Sized or Dilated Pulmonary Artery

Clinical Findings. The clinical findings are similar to those in the Eisenmenger complex in that cyanosis is minimal and may not be recognizable unless the arterial oxygen saturation of a peripheral artery is determined.

Fluoroscopy and Roentgenography. Usually there is a bulge in the pulmonary artery segment with increased pulmonary vascular pulsations.

Angiocardiography. There is simultaneous opacification of the aorta and of the pulmonary artery and more or less complete filling of the ventricular cavity. The opacification of the pulmonary artery is much more marked than that of the aorta.

Catheterization. There is a marked increase in the arterial oxygen saturation of the right ventricle as compared to the right auricle (more than 4 volumes per cent). If the catheter enters the aorta and the pulmonary artery, the pressures and the oxygen saturation are approximately the same. It is easier to enter the pulmonary artery than the aorta.

Atresia or Marked Hypoplasia of the Ascending Aorta with or without Mitral Atresia or Stenosis

Clinical Findings. Cyanosis is present. There is marked enlargement of the heart. Murmurs are variable and are not diagnostic. The infant is seriously ill and usually expires before four to five months of age.

Fluoroscopy and Roentgenography. There is marked enlargement of the transverse diameter of the heart. The pulmonary artery area may be straight or convex. The pulmonary vascular markings may be within normal limits. The right auricle and right ventricles are enlarged.

Angiocardiography. Dye enters the right auricle, right ventricle and pulmonary artery and then passes through the ductus arteriosus into the descending aorta. The latter may be visualized before the ascending aorta and its branches.

Catheterization. There are no characteristic findings.

Anomalous Entrance of All Pulmonary Veins into the Right Auricle, Venae Cavae or Coronary Sinus

Clinical Findings. Dyspnea is an outstanding finding. Cyanosis may not be clinically evident until cardiac failure ensues. There is marked

cardiac enlargement. A systolic murmur over the precordium is usually present.

Fluoroscopy and Roentgenography. There is marked enlargement of the transverse diameter of the heart. The pulmonary vascular pulsations are increased. The pulmonary artery segment is convex. The right auricle, right ventricle and pulmonary artery are large. If the pulmonary veins enter the venae cavae, the diagnosis can be strongly suspected by noting a double shadow at the widened base of the heart due to the shadow of the venae cavae and of the pulmonary veins.

Angiocardiography. This reveals enlargement of the right auricle, right ventricle and pulmonary artery. The characteristic sign is the late reopacification of either the right auricle or the venae cavae or their tributaries.

Catheterization. There is high arterial oxygen saturation of the venae cavae, the innominate vein or of the right auricle which is almost identical with the peripheral arterial oxygen saturation. The catheter may enter the anomalous pulmonary vein and obtain full saturation.

Arteriovenous Pulmonary Aneurysm

Clinical Findings. Because of the shunt of nonoxygenated blood into the pulmonary veins and therefore a right-to-left shunt, cyanosis is one of the cardinal findings. The heart is usually not enlarged. A continuous systolic and diastolic murmur or at times only a systolic murmur is present, heard best over the area of the shunt. A careful search for this murmur should be made over both lung fields. Hemangiomas may be seen over the body.

Fluoroscopy and Roentgenography. The heart is usually of normal size. A pulsating opaque area may be noted if a careful study is made in the posteroanterior and right and left anterior oblique views.

Angiocardiography. Dye enters the lung in the area of anastomosis between the pulmonary artery and pulmonary vein. If one view does not reveal this opacified area, the patient should have angiocardiograms in all three views.

Catheterization. There are no evidences of an intracardiac shunt or increased pressures in any of the chambers.

SUMMARY

We have presented what appeared to us to be the most important symptoms and signs and certain laboratory aids in the diagnosis of the most important cyanotic types of congenital malformations of the heart. We have purposely omitted a number of unusual and bizarre types of these malformations, and have not discussed controversial issues and some additional laboratory tests presently being used.

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ANESTHESIA FOR CARDIAC SURGERY IN CHILDREN

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The drama and tension accompanying surgery of congenital cardiac anomalies seems to have affected adversely the anesthesia for these conditions. The occurrence of occasional extrasystoles or other arrhythmias that may accompany manipulation of the heart or great vessels is a terrifying experience. Attempts to prevent or control these arrhythmias have led to the use of a multiplicity of toxic drugs of doubtful value. The scientific approach has so gripped the imagination that the art of simple anesthesia is rapidly becoming lost in confusing and conflicting reports of "magic" drugs.

In September 1946, when we administered anesthesia for our first congenital heart operation, "cardiac arrest" had not reached its present popularity. We were not concerned with resuscitating a heart in asystole and were able to concentrate on preventing a death on the operating table. No "emergency drugs" or resuscitating apparatus were in the operating room. The problem seemed relatively simple. Three basic requirements had to be met: (1) adequate oxygenation and adequate removal of carbon dioxide; (2) a quiet operative field; (3) careful attention to fluid replacement. After seven years' experience in administering anesthesia to more than 740 children undergoing corrective or palliative cardiac surgery, we see no need to change our original concept or unnecessarily complicate a simple technique.

Accurate diagnosis and careful preoperative preparation are essential. The critically handicapped, cyanotic child is not apt to survive repeated exploratory operations. Definitive treatment must be completed at the first operation. Preoperative preparation includes preparing the child nutritionally and psychologically for this hazardous operation. Psychologic preparation begins at his first visit to the clinic and is continued until operation.

Unless the child is in a critical state of oxygen want, any intercurrent infection or recent upper respiratory infection is an absolute contraindication to anesthesia. Occasionally, an infant is in such a critical state of hypoxia that an operation must be attempted in spite of infection. In such cases, antibiotics are administered before and after operation. Because of the hopeless outlook of many congenital heart lesions, exploratory operation should be attempted if the diagnosis is in doubt. These questionable cases increase the mortality tremendously, but occasionally one is rewarded by improving what seemed to be a hopeless situation.

TYPES OF ANOMALIES EXPLORED

The 743 patients operated upon for congenital heart disease at the Children's Memorial Hospital in Chicago are classified according to the

TABLE 10. *Anomalies Found at Operation*

	NUMBER	DEATHS	PERCENTAGE MORTALITY
Cyanotic Group			
Tetralogy of Fallot			
Aortic-pulmonary or subclavian-pulmonary anastomosis			
2 weeks–3 years	151	23	15.2
3 years–16 years	190	6	3.1
Total	341	29	8.5
Pure pulmonary stenosis			
Pulmonary valvulotomy			
23 days–3 years	19	1	5.2
3 years–16 years	22	0	0.0
Total	41	1	2.4
Tricuspid atresia			
Aortic-pulmonary or aortic-subclavian anastomosis			
11 days–3 years	15	8	53.3
3 years–16 years	5	0	0.0
Total	20	8	40.0
Exploratory			
No corrective procedure	27	13	48.1
Total of cyanotic group	429	51	11.8
Noncyanotic Group			
Patent ductus arteriosus			
Ligation of patent ductus	21	0	0.0
Division of patent ductus	237	0	0.0
Total	258	0	0.0
Coarctation of aorta			
Excision of coarctation	38	0	0.0
Double aortic arch			
Division of double aortic arch	18	5	27.7

anomaly found at operation, as shown in Table 10. This table also shows the operative and postoperative mortality. Children who died at some later date, after being discharged from the hospital, are not included in these statistics.

The operative risk for children with patent ductus arteriosus or coarctation of the aorta is slight. Of almost 300 children who had corrective surgery for these conditions, not one died during or after operation. Since the operative risk is much greater for adults with these congenital lesions, it is advisable to perform operation during childhood, even if subjective symptoms are negligible.

Children with cyanotic heart disease or vascular rings obstructing the trachea present a much graver risk. The pathologic changes make adequate oxygenation an impossibility in some cases, and difficult in all cases. Unless an infant is in a critical state of hypoxia, operation is usually postponed until after the age of three. Hence cyanotic infants fall into the class of poor surgical risks. Several infants were so hypoxic that they expired an hour or two before scheduled operation.

PREOPERATIVE PREPARATION

A "get-acquainted" visit is made the day before operation. The toys, dolls and story books with which the young patient may be playing are noted and admired. The conversation seems to turn naturally to "magic" balloons that Doctor Bob or Joe has upstairs and will let Mary blow up the next morning. Older children often ask intelligent questions about the anesthesia, and are given simple but truthful answers. This is a part of the psychologic preparation begun at their first visit. Parents are frequently present at this visit, and they too may need a few comforting words.

Estimation of the physical and mental status is made in order that preoperative medication may be "tailored" to fit the individual needs of the patient. Parents, if present, are warned not to give the child any liquids or food the morning of operation. Lay people seldom realize the danger of aspiration from a full stomach during anesthesia; consequently, too many children "go to heaven" with a full belly. Fluids by mouth are discontinued six hours before operation. Since this restriction may start between 2 and 6 A.M., the child may be without oral fluids for a much longer period, depending on the time of operation. The resulting dehydration must be corrected by intravenous fluids. Normal fluid balance is particularly important in children with cyanotic heart disease, since dehydration may cause thrombosis. On the other hand, excessive intravenous fluids must be avoided, because they may cause cardiac decompensation.

Premedication

We hesitate to use the term "premedication," because it seems to imply that the sedative drugs administered preoperatively are not a part of the anesthesia. Such is not the case. The nonvolatile drugs administered pre-

operatively are as important to the anesthesiologist as is the incision to the surgeon. Although morphine has been administered to all older children since 1946, it has been administered to the infants in this series only during the past six years. In 1946, infants were given Nembutal or Seconal as a sedative.[7] The effect of barbiturates on infants was unpredictable and unsatisfactory, and their use has been discontinued. Since 1947 morphine has been administered to all cardiac patients preoperatively. Scopolamine is administered with the morphine, usually in the ratio of 1 to 25, as advocated by Waters many years ago.[9] Atropine, which was used extensively in children under five years of age during the first few years of this series, is seldom used today.[8] The cerebral depressant effect of scopolamine and its minimal effect on heart action make it superior to atropine, in our opinion.

The determination of dosage depends on the patient's level of reflex irritability. Since this level parallels fairly constantly the metabolic ac-

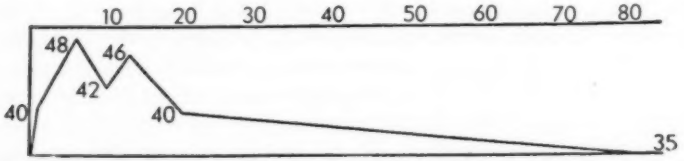

Fig. 51. Curve of normal metabolic rate throughout life, estimated in calories per hour per square meter of body surface. The curves of oxygen demand and reflex irritability are exactly parallel. (From A. Guedel: Inhalation Anesthesia. New York, The Macmillan Company.)

tivity, and since metabolism varies with the age, the most important single factor in determining the optimal dose is the age of the child.[2] Figure 51 graphically illustrates the variation of metabolism with age. Since a child may be overweight because of lowered metabolism, the fallacy of a dosage chart based on weight alone is clearly seen. Failure to recognize this basic principle often results in underpremedication, and may add an extra hazard to anesthesia.

It is our aim to lower the level of reflex irritability of a patient to a more or less fixed optimal point of metabolic depression. The optimal point is characterized clinically in a child by "mellowness" and lassitude. The child is drowsy, but not asleep. If undisturbed, he may doze from time to time. If disturbed (e.g., by a resident listening to his heart or examining him), he is only mildly interested in the procedure. This highly desirable state of metabolic depression is achieved, in the average cardiac patient, by relatively generous amounts of premedication, as shown in Table 11.

These doses are not absolutely fixed. They are only *suggested* starting points at various ages, and should be increased or decreased according to

the experience of the anesthesiologist. They merely indicate what we consider a generous dose. Because of differences in metabolic activity, a nine year old child may be more depressed than a six year old child if given the same dose (morphine sulfate, 1/8 grain, and scopolamine hydrobromide, 1/200 grain), in spite of the fact that the nine year old *weighs* much more.

TABLE 11. *Premedication*

AGE	DOSAGE	
	Morphine Sulfate	*Scopolamine Hydrobromide*
14 days	0	1/400 grain (0.16 mg.)
2 months	1/80 grain (0.8 mg.)	1/400 grain (0.16 mg.)
6 months	1/64 grain (1.0 mg.)	1/400 grain (0.16 mg.)
1 year	1/32 grain (2.0 mg.)	1/400 grain (0.16 mg.)
2 years	1/24 grain (2.7 mg.)	1/400 grain (0.16 mg.)
3 years	1/16 grain (4.0 mg.)	1/400 grain (0.16 mg.)
4 years	1/12 grain (5.4 mg.)	1/300 grain (0.22 mg.)
5 years to puberty	1/8 grain (8.0 mg.)	1/200 grain (0.33 mg.)
Past puberty	1/6 grain (10.8 mg.)	1/150 grain (0.43 mg.)

Many anesthesiologists use such homeopathic doses that this basic fact is not clinically recognizable.

CHOICE OF AGENTS AND TECHNIQUE

Safe anesthesia for cardiac surgery demands agents and techniques which (1) allow rapid and smooth induction with a high oxygen tension; (2) permit minute-to-minute control of depth of anesthesia; (3) ensure an adequate airway, so that the lung may be collapsed or expanded instantly; (4) remove excess carbon dioxide; (5) disturb the physiology as little as possible; (6) make possible a rapid return to consciousness without unpleasant side reactions; and (7) produce a quiet operative field, undisturbed by respiratory movements.

Cyclopropane as the principal agent, administered by the to-and-fro absorption technique with completely controlled respiration, most nearly satisfies these requirements. We recognize that neither the agent nor the technique is perfect, but we know of no other agent or combination of agents or techniques that so nearly approaches the ideal anesthetic combination for these cases.

Rapid and smooth transition from consciousness to unconsciousness is produced by administering cyclopropane with a to-and-fro system. Several sizes of face masks and soda lime canisters must be available in order to avoid excessive dead air space. Colored balloons (or beach balls) are used for breathing bags because of the psychologic effect. Restraints are not used. After induction a polyethylene tube is inserted into the saphenous vein for the intravenous administration of fluids and medication,

as indicated. During operation, blood lost is replaced with whole blood, which has proved more desirable than plasma as a volume expander, even for cyanotic children with red blood cell counts above 9,000,000. The intravenous tube is left in place after operation until the child is taking nourishment normally.

When the first plane, third stage, of anesthesia is attained, ether is added to the mixture. Ether produces relaxed vocal cords and permits careful inspection of the larynx and unhurried intubation with a suitably sized endotracheal tube. Three sizes of endotracheal tubes are usually laid out on the table, and the final choice of size is made only after laryngoscopy. Lubricant is no longer used. The patient's own secretions seem to be adequate and more desirable than the introduction of Vaseline or KY jelly into the trachea. Laryngeal edema, which in 1950 we reported as an annoying and serious complication, is now rare. This is undoubtedly due to several factors: (1) improved technique; (2) better selection of tube size (neither too large nor too small); (3) sterilization of tubes (boiling, instead of cold solutions); (4) improved canister brackets (so that the position of the tube does not shift in the larynx with controlled respirations); and (5) no foreign lubricant.

After intubation the anesthesia is maintained entirely with cyclopropane and oxygen. The patient is "carried" in plane one. Deep anesthesia is neither necessary nor desirable.

Probably the most important part of the technique is controlled respiration, as soon as the pleural cavity is opened. Since the chest is open and the normal intrapulmonic pressure no longer obtains, controlled respiration does not interfere with the return venous flow of blood to the heart to the extent that it would with a closed chest. We use a "breathing" rate that is rapid and vigorous enough to immobilize the diaphragm, if at all possible. This rapid rate for controlling respirations seems unsound physiologically. Clinically, however, the results have been satisfactory.

In some instances the child is so cyanotic preoperatively that complete control is impossible to achieve. Since this inability to control respirations is a danger sign, we seldom use curare, because we do not want to mask this warning signal. These children are often inoperable because of existing pathologic changes.

Eastwood and his co-workers have shown that a patient with an open thorax must be ventilated more vigorously than a normal person. From their well controlled studies they conclude that "serious acidosis due to inadequate alveolar ventilation was always present in unassisted intrapleural operations and that acidosis could be completely prevented by assistance to ventilation. This ventilation had to exceed values considered 'adequate' for normal conscious man."[3]

ARRHYTHMIAS

Disturbances of cardiac rhythm are among the most disconcerting complications that occur during heart surgery. They are usually of little consequence if one remembers that they are warning signs or safety signals for the heart. A few extrasystoles or a change in rate usually means that the myocardium is not receiving enough oxygen, or that it is building up too much carbon dioxide. Immediate steps must be taken to increase the oxygen supply and remove the excess carbon dioxide. Myocardial depressants, such as procaine or Pronestyl, are not indicated and may prove harmful.

Johnstone[5] demonstrated that hypercarbia during cyclopropane anesthesia in man regularly produced ventricular arrhythmias which disappeared on the reduction of the carbon dioxide level, but were unaffected by the addition of oxygen alone.

Ziegler[10] analyzed the electrocardiographic tracings recorded during cyclopropane anesthesia administered to 175 children with tetralogy of Fallot and 25 children with patent ductus arteriosus. He concluded that although some cardiac disturbance occurred in about 80 per cent of the cases, most of the disturbances were of little clinical significance. Seven deaths occurred in the cyanotic group, all apparently due to anoxia. We have pointed out in previous papers and again stress the fact that the most frequent cause of death in these patients is severe hypoxia or true anoxia. The pathologic changes in such severely cyanotic children prevent adequate oxygenation of the blood in many patients.

Electrocardiographic tracings made at the Children's Memorial Hospital by Dr. Katherine Lewis[6] demonstrated that arrhythmias were usually associated with some technical difficulty with the anesthesia which resulted in hypercarbia and hypoxia. Children with patent ductus arteriosus are easily oxygenated and almost never have arrhythmias; however, depression of the S-T segment, denoting inadequate oxygenation, was occasionally noted if the controlled respiration was not rapid or vigorous enough.

These and many other reports on the use of cyclopropane, coupled with our personal experience with this agent for thoracotomies during the past fourteen years, lead to only one conclusion: "The fear of sudden death during cyclopropane anesthesia is largely unjustified if proper precautions are taken to prevent the accumulation of carbon dioxide and the occurrence of hypoxia."

Arrhythmias initiated by nerve stimulation have been exceedingly rare. Early in this series, cocaine was applied locally or procaine was injected into the pericardial sac to prevent "reflex" arrhythmias. The electrocardiographic studies at the Children's Memorial Hospital cast so much doubt on the value of these drugs for this purpose that we rarely have

used them in recent years. Gross[4] has likewise discontinued the routine practice of injecting procaine into the pericardial sac.

OTHER ANESTHETIC CONSIDERATIONS

Patients with a history of decompensation are poor risks and should be treated in the same way as any patient with potential heart failure about to be subjected to surgical procedure. Digitalization is done when indicated. One patient with coarctation of the aorta had a pulsus bigeminus of long standing preceding operation. Near the end of operation, acute heart failure developed, with cardiac dilatation and pulmonary edema. Rapid digitalization and the intravenous administration of 50 per cent dextrose proved efficacious.

Any period of hypotension is dangerous and may be the cause of a cerebral accident, especially in the presence of polycythemia. A marked drop in blood pressure may occur when the aortic clamps are removed after excision of a coarctation or when a Potts-Smith clamp is opened after an aortic-pulmonary anastomosis. Slow opening of the clamp, especially in children with a small aorta, is imperative, and rapid infusion of whole blood is sometimes done to correct this hypotension.

One of the most critical periods of anesthesia is immediately after the completion of the operation. An anesthetized patient may be thrown into shock by rapidly turning him from the lateral to the supine position. The intratracheal catheter is not removed until the child begins to react. Patients who have suffered from asphyxia during operation breathe poorly for a time and may have hypotension. Such patients are kept on the operating table until respirations are normal and they are out of shock. Occasionally a child has been kept on the table for several hours after completion of the surgical procedure. Artificial respiration with 100 per cent oxygen is administered. Respiratory stimulants are never used. No drug is superior to oxygen for the treatment of hypoxia.

COOLING

Cooling of severely hypoxic children to a body temperature several degrees below normal, in order to reduce the metabolism and possibly the excitability of the myocardium, has been of great benefit. Since May 1948 the temperature of almost every child subjected to a major surgical procedure at the Children's Memorial Hospital has been carefully controlled. A rubber mattress is placed on the operating table under the child (Fig. 52). Cold tap water or ice water is run into the mattress as soon as the child is asleep, and the rectal temperature is maintained between 97° and 100° F. A rectal thermometer, in place during the entire operation, gives an accurate record of the temperature at all times. Cy-

anotic children usually have their body temperature lowered to between 98° and 94° F. Though an occasional child has had his temperature lowered to the middle 80's, we are not yet convinced that a temperature much below 90° F. is either indicated or safe.

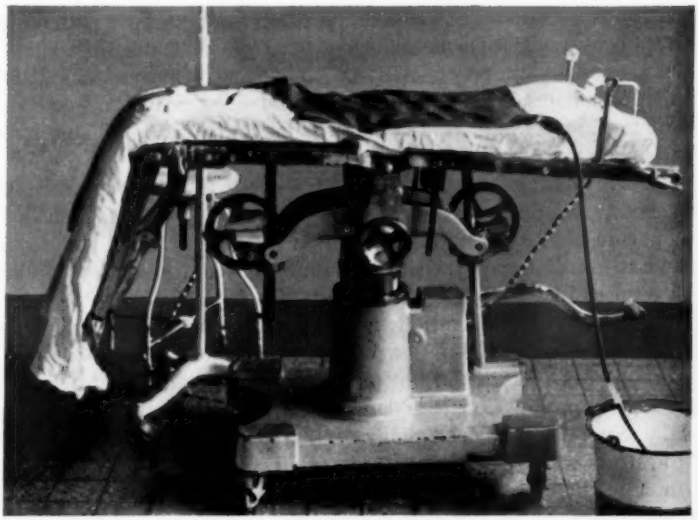

Fig. 52. Water mattress.

POSTOPERATIVE CARE

Children in the cyanotic group are routinely placed in an oxygen tent when returned to their beds. In most instances the oxygen is discontinued in twenty-four to forty-eight hours. The majority of the children in the noncyanotic group do not require oxygen postoperatively. Fluid and electrolyte balance are maintained intravenously until the child receives adequate oral fluids and food. The child decides when he wants to eat and drink. Many start taking nourishment within a few hours after operation. Antibiotics are administered routinely during the postoperative period. Other postoperative treatment depends upon the complications, if any.

Postoperative Complications

Postoperative complications have been much more frequent in the cyanotic group than in the noncyanotic group, with one exception. Infants with a double aortic arch are not cyanotic, but may have severe tracheal obstruction. This obstruction is usually at or near the carina, and may be accompanied by pathologic changes in the tracheal rings.

This makes it difficult to maintain an adequate airway, both during and after operation. Tracheotomy is seldom helpful, owing to the location of the obstruction. Even endotracheal insufflation through fine polyethylene tubing has not been entirely satisfactory in maintaining adequate respiratory exchange.

Many of the children in the cyanotic group have extensive pathologic changes before operation. Pathologic changes in the lungs have predisposed to pneumonic processes which, in several instances, were fatal within forty hours after operation. Cerebral hemorrhage and cerebral thrombosis are the next most common fatal complications. These have usually been preceded by cerebral accidents preoperatively.

Right heart failure was the cause of a few deaths in this series. Cerebral anoxia occurring during operation was irreversible in two instances. Tension pneumothorax, hemorrhage from an intercostal artery, and sepsis secondary to infection at the site of cannulization of the saphenous vein, each resulted in a death early in our experience. Fatalities in the group in which exploratory operations were performed were all secondary to severe hypoxia that could not be relieved surgically.

Complications which did not end fatally were of a wide variety and were mostly minor. Cough or laryngeal edema was most frequent. It usually responded to high humidification in the oxygen tent or treatment in the steam room. Six patients were subjected to tracheotomy; several of these might have recovered without tracheotomy, but we favor early tracheotomy in severe laryngeal obstruction. Atelectasis occurred a number of times, but was relieved by crying or coughing and required no further treatment. Cerebral hypoxia with coma or spasticity occurred in several patients who eventually recovered completely. Pneumothorax, hemothorax, hemopneumothorax and effusion occurred a number of times and, as might be expected, were more common before the institution of routine chest drainage.

Infrequent complications have included tonsillitis, measles, drug rash, enteritis, pyelonephritis, transfusion reaction and other similar complications occurring in any large series of surgical cases from a children's hospital.

SUMMARY

The anesthetic management of infants and children undergoing cardiovascular surgery at the Children's Memorial Hospital in Chicago for the past seven years is reviewed.

Generous doses of morphine and scopolamine are recommended for premedication.

Cyclopropane, administered by the to-and-fro absorption technique with controlled respirations, is still favored by our group.

Adequate oxygenation and carbon dioxide elimination are considered the most important factors in preventing "cardiac arrest" and decreasing the incidence of cardiac arrhythmias. Procaine is considered of doubtful value for the prevention of cardiac arrhythmias.

Hypothermia, introduced in 1948, is the only major modification in the anesthetic technique used for all cardiovascular surgery at the Children's Memorial Hospital since 1946. Its importance is secondary only to adequate oxygenation and adequate removal of excess carbon dioxide.

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SURGICAL TREATMENT OF PATENT DUCTUS ARTERIOSUS

WILLIS J. POTTS, M.D.

A discussion of the surgical treatment of patent ductus arteriosus in a pediatric journal may at first glance seem out of place. However, if it is appropriate, and it undoubtedly is, for the surgeon to listen to the continuous "humming top" murmur of each patient he is to operate upon and to feel the characteristic thrill, then it is not inappropriate for the pediatrician likewise to give brief attention to some of the basic principles of surgical care.

In August, 1953, it was only fifteen years since the first patent ductus arteriosus was successfully closed by Gross.[1] In retrospect it seems strange that this congenital deformity should have resisted surgical treatment for so many years, especially since today its correction is a commonplace procedure. Actually, this rapid progress has been due in large measure to concurrent development in other branches of medicine, notably pediatric cardiology, thoracic surgery and anesthesia.

DIAGNOSIS

Diagnosis of a typical patent ductus is relatively simple and can be made tentatively even by a surgeon. A diagnosis can be made in most instances on the basis of ten specific findings:

1. The child has a characteritic, noisy, raucous, "humming top," continuous murmur going through diastole and heard best at the second interspace at the left of the sternum.
2. A palpable thrill, noted best with the hypothenar edge of the hand, is felt in the same area.
3. The pulse pressure is high.
4. A "water-hammer" pulse is felt over the femoral arteries.

From the Department of Surgery of the Children's Memorial Hospital, Chicago.

5. A capillary pulse is often visible in finger tips or lip compressed with glass slide.

6. Roentgenograms of the chest show increased vascularity of the lung fields, often some enlargement of the heart, and not infrequently a convexity in the region of the pulmonary segment along the left base of the heart.

7. Electrocardiograms usually show a balanced axis.

8. The child is apt to be undersize and underweight.

9. Many children seem to be excessively active and full of spirit.

10. A child with a typical uncomplicated patent ductus arteriosus is never blue.

Such a brief word picture of the typical patent ductus describes the vast majority of cases. Nevertheless, the danger of going astray diagnostically makes it a good rule, which with us is inviolable, that every patient be studied by the department of cardiology before being subjected to operation.

INDICATION FOR OPERATION

A reasonable and altogether justifiable question asked by parents is this: "What will happen to our child if we do not have the operation?" Before one can give an answer they are apt to add, "We hate to have such a big operation when our child is so well and so active." Sympathetically, one must explain the reasons for advising operation. Since the dangers of bacterial invasion have been largely eliminated, the prime purpose of obliterating the ductus is for protection of the heart muscle. In earlier days, when ductus surgery was still in the premature stage, watchful waiting was advised for patients with minimal findings. Today, operation is advised for all patients with a patent ductus arteriosus. Difference in advice for one patient or another is controlled by the child's condition and by sociological and familial considerations.

Most patients with a patent ductus fall into one of three categories: (1) The child with considerable enlargement of the heart and markedly vascular lung fields should have prompt operation, because each year will increase the hazard of operation. Eventually the heart muscle will break, and the point of no return will have been passed. (2) The child with bacterial arteritis should be given the benefit of early operation. If the infection is active, vigorous antibiotic therapy is indicated until the infection is controlled. It is more desirable from the standpoint of improved operative risk if the operation can be delayed a reasonable time after the infection has subsided. Immediate operation is indicated if a definite past history of bacterial arteritis is obtained. In all instances of previous bacterial involvement the ductus should be divided. (3) What about the group of children—and it constitutes the majority—who have a patent

ductus and nothing more? If the murmur is typical, if a mild thrill is palpable, if the heart is not enlarged or is slightly enlarged, and if the lungs are mildly vascular, we now unequivocally advise operation at a convenient but specific time lest the parents delay indefinitely. It is explained that the operation is purely a prophylactic procedure.

The teaching and practice of pediatricians these days tend so much towards prophylaxis against future trouble that most parents, after suitable explanations, are willing to have their seemingly perfectly well child undergo an extensive operation. Interestingly enough, many parents who were hesitant in making up their minds express genuine gratitude after operation that the worrisome defect has been corrected. Naturally all parents want their child to be normal.

Fishman and Silverthorne[2] reported the case of a woman with a known patent ductus arteriosus who came to postmortem examination at the age of seventy-five years. The ductus was 3 mm. in diameter at the aortic end and 4 mm. at the pulmonary end. This diameter is considerably smaller than the average ductus in our experience, which averages approximately 7 mm. in diameter, outside measurements. The case, although a singular one, does indicate that the heart is a rugged mechanism which can withstand much abuse.

It is comforting to us who make artificial ductus between the aorta and the pulmonary artery for the relief of cyanosis due to pulmonary stenosis to know that a person can live to seventy-five years of age with a 3- to 4-mm. ductus—the size of the opening it is our policy to make in the surgical treatment of the tetralogy of Fallot.

AGE FOR OPERATION

At birth the ductus has fulfilled its function and should close spontaneously. Christie[3] made a detailed postmortem study of the ductus arteriosus in babies and found 44 per cent of ductus open at one month and 2 per cent open at eight months of age. The fact that so many ductus are open during the early months of life is a satisfactory answer to why one pediatrician hears a loud systolic murmur—the diastolic phase is not often audible in infants—and the next pediatrician hears no murmur. Both were right.

At age one year most ductus which are going to close spontaneously have done so. At two years of age, and certainly at three, there is little reason to hope for spontaneous closure. We therefore consider the most suitable time for operation between three and seven years. The operation is infinitely simpler in a child than in an adult; the ductus is longer, more pliable, less apt to have aneurysmal dilatations, and more easily freed from the surrounding structures. Until the past few years the possibility of a huge patent ductus causing heart failure during early infancy was not fully appreciated. Ziegler[4] emphasized the importance of a patent ductus in infancy, and Mustard[5] reported 4 patients operated upon successfully

during infancy. A number of patients in this series have been operated upon during the first year of life, notably two children, one age five months and another age eleven months, both with tremendous enlargement of the heart (Fig. 53). The five month old child had a minimal

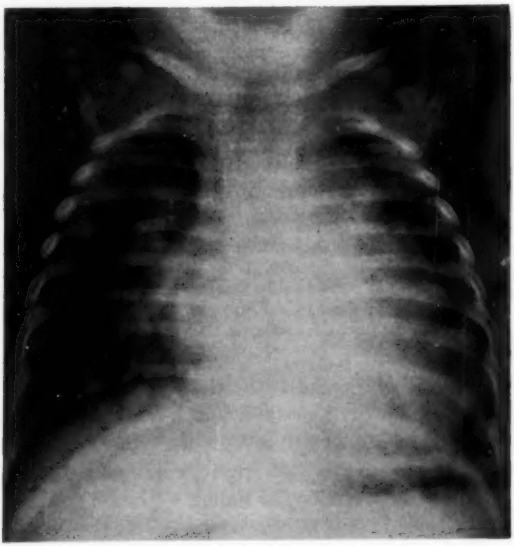

Fig. 53. Greatly enlarged heart in an 11 month old infant with a huge patent ductus.

diastolic murmur, in spite of the fact that at operation a ductus was divided which was practically equal to the aorta in diameter.

PREOPERATIVE CARE

Upon admission to the hospital every child is examined carefully for signs of upper respiratory infection or contagion by an impartial pediatric resident who has no interest in the operative schedule. When folks have travelled long distances and their child contracts a cold en route, it is trying to the parents economically and hard on their morale to be ent home. When it is explained, however, that the child might suffer postoperative pneumonia, common sense prevails. During the early spring months at least 25 per cent of children must be turned away for later appointments for surgery because of respiratory and childhood diseases. The child is routinely admitted to the hospital forty-eight hours before operation as a further check on operability. Incidentally, this time affords an opportunity to energetic members of the resident staff, clerks and interns to familiarize their ears with the sound of the classical murmur.

If the child has not been briefed on the object of its hospitalization, this is done during the preoperative period. The importance of psychologic preparation for operation cannot be overemphasized. Nothing is more flattering to a child than to be treated as an intelligent human being. The younger child is told in words of one syllable that it will have a ride on a cart, will go upstairs and there will see a lot of people with masks on their faces. It will be given a balloon to be blown up, will go to sleep, feel no pain, and will wake up back in the room where Mother will be waiting. After the usual explanation to a precocious boy, eight years old, he still looked dubious and finally said, "Just tell me exactly what you are going to do and I won't be nervous." A physician sent in his twelve year old daughter for operation, but told her that she was coming in for a special examination. How to win disrespect and lose influence!

Preoperative medication consists only in a fairly liberal hypodermic injection of morphine balanced with the proper amount of scopolamine. Sedatives such as phenobarbital are rarely given to the child before operation. The dose of morphine is sufficiently large so that the child is free of anxiety, sleepy and only mildly interested in its surroundings. When the child is laid on the operating table, if the psychologic preparation has been sufficient and the morphine and scopolamine adequate, no one will have to restrain the child while it is being put to sleep. There are a few exceptions!

TYPE OF OPERATION

It was a tremendous accomplishment when Gross succeeded in tying a single piece of string around a patent ductus. After closing the first two ductus with single ligatures and hearing after operation a remnant of the original murmur, Gross decided to use two ligatures. To these was added a piece of umbilical tape and later a wrapping with cellophane to promote adhesions which might aid in closing a small remaining fistula. Ligation "in continuity" will occasionally lead to re-establishment of the lumen as the ligature slowly cuts through the vessel wall. Furthermore, it is difficult when ligating a ductus to know how much pull to exert on the ligature—too much and the vessel wall is immediately cut with disastrous consequences; too little and the ductus is incompletely closed.

In our early work we ligated twenty-one consecutive ductus. Present follow-up examinations reveal no evidence of recurrence, but we still are a bit concerned about the mass of nonabsorbable silk and umbilical tape which lies buried between the pulmonary artery and the aorta and directly over a bronchus.

In 1947, multitoothed clamps involving a new principle were devised[6] and proved safe and effective for clamping and holding the ductus while it is being cut and sutured. These clamps (Fig. 54) have multiple teeth

(forty to 1 inch) in the opposing jaws. When the clamp is closed, these teeth embed themselves in the wall of the vessel, but do not injure it. The hub of the clamp is so constructed that the teeth can come together, but not interdigitate more than a small fraction of a millimeter. The clamps are thin and take up little room in the limited space between the aorta

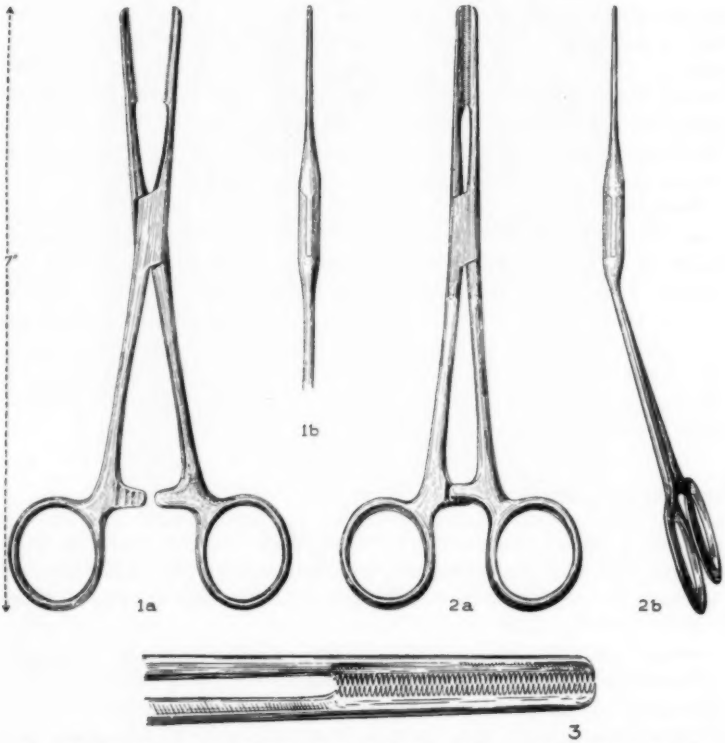

Fig. 54. Drawings of the clamps. *1a* and *1b*, The clamp used on the pulmonary end of the ductus. *2a* and *2b*, The angulated clamp used on the aortic end of the ductus. 3, A much enlarged drawing to illustrate the principle of many tiny teeth in the opposing jaws.

and the pulmonary artery. If the lappet of pericardium has been well drawn back and the loose connective tissue has been adequately removed from the ductus, the clamp well placed will not slip. Since 1947, with the aid of these clamps, 229 consecutive patent ductus in children ranging in age from five months to sixteen years have been divided.

Although we believe the chances of operative hemorrhage are less when the ductus is clamped and divided than when it is ligated and/or trans-

fixed, many surgeons prefer the latter method. The long ductus which is easy to divide and sew is also the one which can be ligated without chance of recurrence; unfortunately, the short large ductus which is somewhat difficult to isolate, clamp and divide is the very one which may recur after any of the techniques of ligation.

ANESTHESIA

Advance in the specialization of anesthesia has made possible rapid progress in all types of chest surgery. When a skillful anesthesiologist is giving the anesthesia—always administered by intratracheal tube—it is no more dangerous to enter the chest than the abdomen. The surgeon today expects from the certified physician-anesthesiologist for the surgery of patent ductus arteriosus smooth induction, constant adequate exchange of gases, never the slightest cyanosis, a steady pulse, a quiet operative field, quick recovery and a minimum of postoperative complications due to anesthesia. Fortunately, this high objective is now approachable.

Much has been written in recent years about cardiac arrest, a euphonious term used when the heart stops beating and the patient dies during the operation. In children who do not have degenerative disease of the coronary vessels and myocardium, cardiac arrest should be extremely rare. A child's heart does not spontaneously stop beating during the violent activities of youth; neither will it stop during operation, provided the child is not excessively poisoned with multiple drugs and too much anesthetic agent, and provided the airway is constantly open so that adequate oxygen may be absorbed and excess carbon dioxide eliminated. If a child bleeds excessively during operation and the blood is not replaced, death is due to hemorrhage and not to cardiac standstill.

OPERATIVE PROCEDURE

Details of operative technique are not a propos in this article, but a few general statements may not be amiss.

The child is placed on the operating table in the supine position and put to sleep. A fairly good-sized polyethylene cannula is inserted into the saphenous vein of the right ankle for the administration of blood. Blood replacement during operation has become routine, and the best way of administering it is by way of the saphenous vein. In this operation, as in all other operations of any magnitude, it is routine to do a "cut down" before beginning operation. To the polyethylene tube is attached a 3-way stopcock so that the blood can be pumped in rapidly in case of emergency. This 3-way stopcock is used in all operations whenever a "cut down" is done. Having this simple mechanism in the system has saved a number of children other than those undergoing heart surgery who would other-

wise have died on the operating table. It is routine to have 500 cc. of blood in the operating room for each ductus operation. More blood is always available from the bank on a moment's notice.

The patient, now intubated, is turned on the right side. We prefer a long posterolateral incision (Fig. 55, *A, B*) to the curved anterior sub-

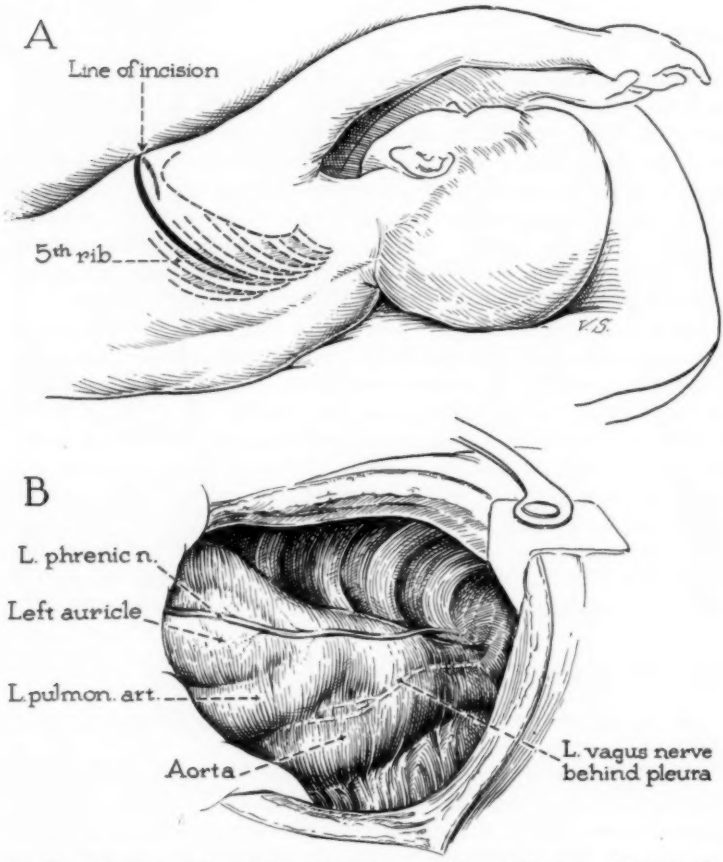

Fig. 55. A, Position of the child on the operating table and the type of incision. *B*, The landmarks which are guides to the position of the ductus.

mammary incision, because we feel that the former gives better exposure of the ductus and the surrounding large vessels—an important feature in case of trouble. The chest is routinely entered through the fourth intercostal space. We never resect a rib for this operation.

The ductus is easily recognized. It lies lateral to the phrenic nerve and

obviously between the aorta and the pulmonary artery (Fig. 55, *C*, *D*). The characteristic palpable thrill is a guide to its location. After the mediastinal pleura has been opened, the vagus nerve is isolated. The recurrent laryngeal branch always courses around the ductus and is an absolutely infallible guide to its position.

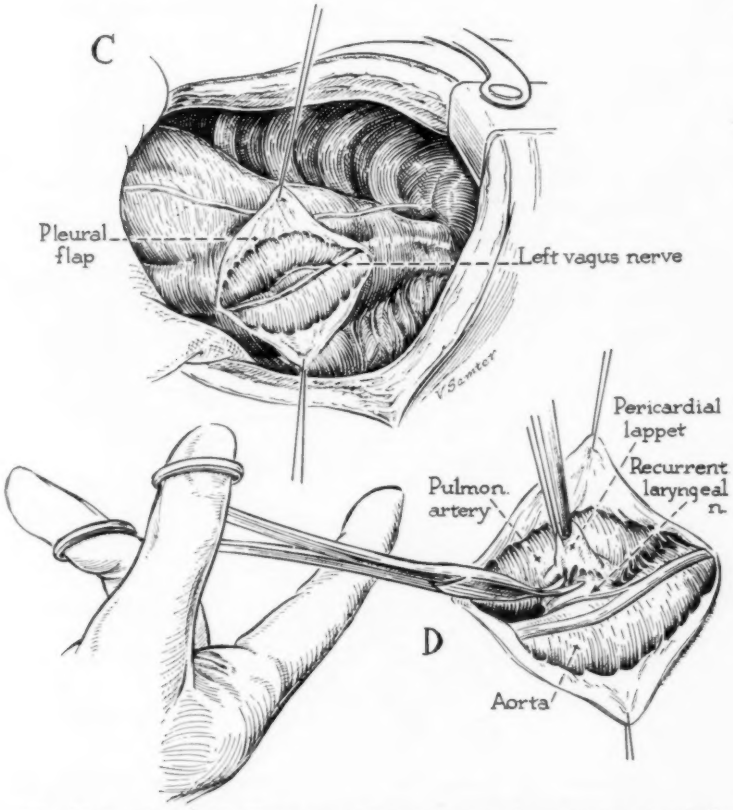

Fig. 55 (continued). *C*, The recurrent laryngeal nerve always courses around the ductus. *D*, The pericardial lappet, often extending to the aortic end of the ductus, is dissected well up on the pulmonary artery.

The important step in the operation is freeing the ductus from its surrounding structures (Fig. 55, *E*, *F*, G). The lappet of pericardium is carefully and thoroughly dissected from the anterior surface of the ductus with sharp scissors dissection. Then the fibrous tissue about the ductus is cut away and the ductus is separated from the bronchus posteriorly. Often at the beginning of an operation it appears that the ductus has no

length at all, but is merely a fistula between the two vessels. However, after all the surrounding connective tissue has been dissected away it becomes happily apparent that the ductus is long enough to clamp and divide.

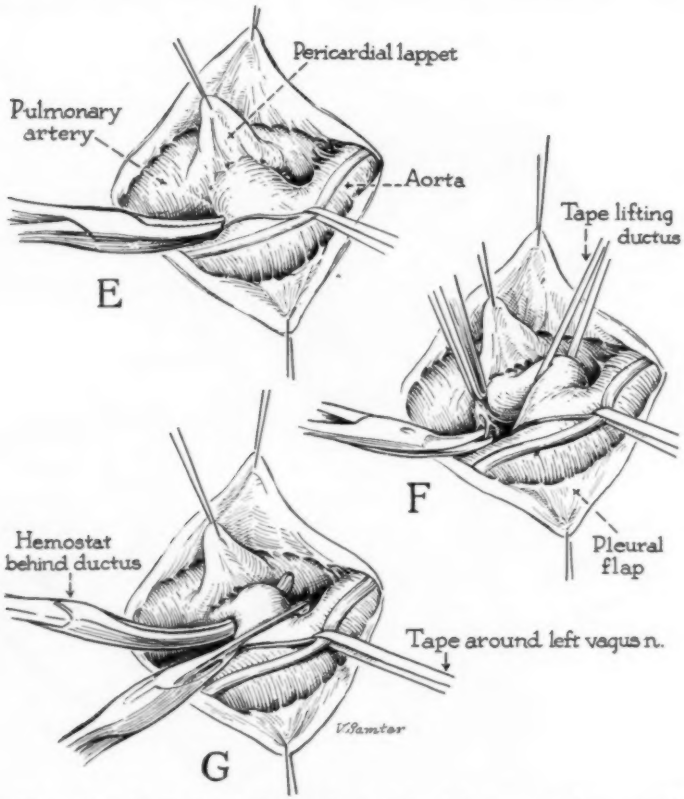

Fig. 55 (continued). *E*, *F* and G, The ductus is freed from its attachment to the structures posterior to it, and all loose tissue is dissected away.

Two clamps are applied to the ductus—the angulated one at its aortic end and the straight one at the pulmonary end. The ductus is cut with a long thin scissors, and the stumps are closed with a double row of continuous sutures (Fig. 55, *H*, *I*, *J*). Since the technique of placing these sutures has been learned there is practically never more than a few drops of bleeding when the clamps are removed.

The chest is drained and closed in routine fashion.

POSTOPERATIVE CARE

The child is returned to its room, where the chest drain is promptly connected with a water-seal bottle. The chest drain, usually left in place for twenty-four to forty-eight hours, has eliminated the necessity of tapping the chest for the removal of serosanguineous fluid. The child is not placed in oxygen after operation.

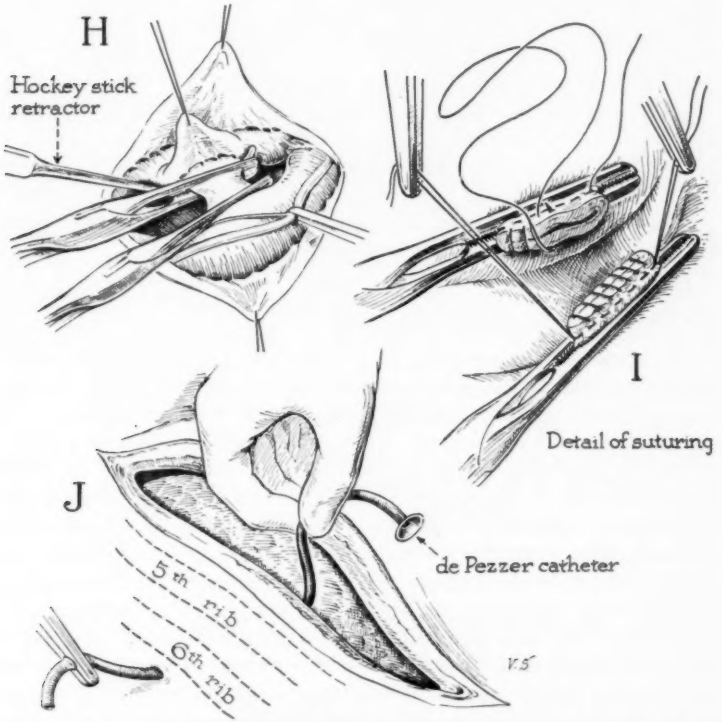

Fig 55 (continued). *H* and *I*, The clamps are in place, the ductus is cut, and the stumps are sewed with silk. *J*, The chest is drained. (Author's article in Archives of Surgery, Vol. 66, published by the American Medical Association.)

Careful watch is kept for signs of respiratory distress resulting from irritation of the intratracheal tube. At the first sign of dyspnea or rasping breathing, fortunately not common, the child is placed in an oxygen tent which is humidified, or is moved to the steam room. High humidity is excellent treatment for any postoperative laryngeotracheal irritation. The child with severe tracheobronchitis is watched closely, because dyspnea may suddenly become alarmingly severe. In 2 cases we have had to do a

tracheotomy. It seems wise to us to do a tracheotomy early, that is, when the child is having continuous respiratory distress not relieved by humidity and mild sedation, rather than wait until the patient is worn out gasping for air.

Other postoperative complications have been of the usual variety. Occasionally a child comes down with a contagious disease to which it was exposed before operation. Coughs, colds, sore throats, penicillin rashes, stitch abscesses, thrombophlebitis from the intravenous tube, and other minor complications arise from time to time and are annoying but not serious. Pneumonia and atelectasis have occurred occasionally, but in no instance have been followed by empyema.

Crysticillin, 300,000 units, is given in one dose daily by hypodermic injection for about one week.

The child decides when and what it wishes to eat and when it feels able to sit up and get out of bed.

Hospitalization varies from eight to twelve days, depending upon the distance the patient has to travel to home.

MORTALITY

There has been no mortality in 250 consecutive patent ductus closed surgically at the Children's Memorial Hospital. Of this group, the first twenty-one were closed by multiple ligation, and the next 229 consecutive cases were divided and sutured. During this time no child with a patent ductus was refused operation, and in no instance when a ductus was found at operation was it necessary to leave the ductus unclosed. Incidentally, the diagnosis made by Dr. Stanley Gibson and associates was correct in 249 cases. The reason for the continuous murmur in the one child who did not have a ductus remains unknown. The reasons for the good fortune in having no mortality are several: first, the ages of the patients varied from five months to sixteen years. The operation is far simpler in children than in adults. However, the patient that most nearly died after operation was an infant five months old. The second reason is, emphatically, skillful anesthesia. No case of even momentary cardiac arrest occurred, and for that good fortune we are indebted solely to the department of anesthesia. The third is excellent postoperative care, for which we are indebted to the watchfulness of the residents and nurses. The fourth is the mythical turn of the wheel of fortune. Operative mortality is like a shadow which relentlessly follows every type of surgery no matter how minor, and some day in the surgical treatment of patent ductus the axe of misfortune will fall. Recognizing the inevitable, when parents ask about the danger of the operation, they are told that no operation is without some danger and that the mortality in this particular operation is less than 1 per cent.

Surgical closure of the patent ductus arteriosus is one of the most

satisfactory of all types of operations for congenital heart disease. One can truthfully tell the parents that their child has an excellent chance of surviving the operation and after operation will be normal as other children. If the heart is much enlarged (Fig. 56) at the time of operation,

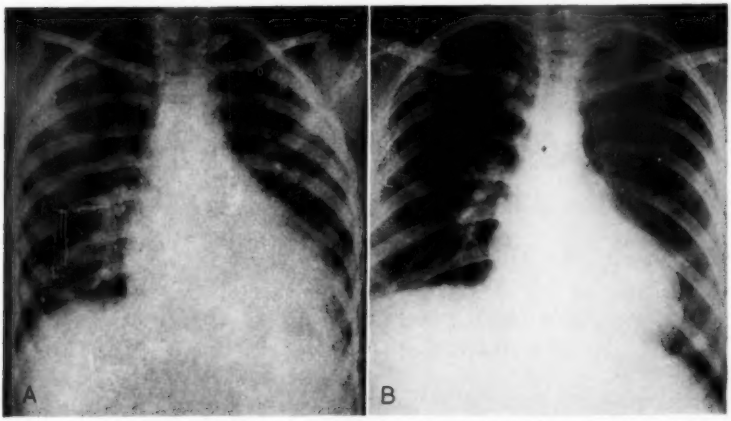

Fig. 56. A, Enlargement of the heart and vascularity of the lung fields in a 7 year old child with a patent ductus. *B*, Five years later, at age 12 years, the heart is actually smaller than it was before the ductus was closed surgically.

one can assure the parents that eventually it will be normal. The heart will coast along, so to speak, until the growth of the child catches up and demands that further heart development is necessary.

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DIAGNOSIS AND MANAGEMENT OF COARCTATION OF THE AORTA IN CHILDREN

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JAMES W. DUSHANE, M.D.

Coarctation of the aorta is not a rare congenital anomaly. According to Abbott's[1] studies, coarctation of the aorta makes up approximately 14 per cent of all congenital cardiovascular anomalies. It has been estimated that this lesion occurs in one of every 2000 persons. If this is true, probably 75,000 persons in the United States have coarctation, a number sufficiently large that most physicians will have opportunities to recognize the lesion if they will look for it.

Coarctation of the aorta should be a subject of particular interest to the pediatrician, since it offers both a challenge and a responsibility to those concerned with the health and welfare of infants and children. It offers a challenge because it is not always easy to establish a diagnosis of this lesion in infants and children, and a great responsibility because the best results from surgical treatment require early diagnosis, which the pediatrician is in the best position to provide.

The fact that coarctation of the aorta does occur has been known for many years, and occasionally the condition has been recognized by astute clinicians. However, because there was no treatment to offer patients, there has been little clinical interest in this anomaly until recently. Most of the early literature regarding this lesion consists of reviews of cases and results of necropsy. Necropsy has shown clearly that coarctation of the aorta is a lesion which, although fairly well tolerated by the young, is fatal among adults. Only 25 per cent of patients having coarctation of

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the aorta have lived more than thirty-five years. The principal causes of death are rupture of cerebrovascular aneurysms; rupture of aneurysms of the aorta, either proximal or distal to the site of the aortic obstruction; cardiac failure resulting from strain on the left side of the heart; and subacute bacterial endarteritis. All these causes of death are directly attributable to hypertension in portions of the body supplied by blood vessels arising from the aorta proximal to the site of obstruction or from altered hemodynamics produced by the aortic obstruction. It is obvious that if coarctation of the aorta is to be treated successfully by surgical means, the lesion must be diagnosed and operation performed before irreversible cardiac and vascular damage has developed.

Blalock and Park[2] in 1944 were the first to suggest that coarctation of the aorta might be treated effectively by surgical means. The first successful operations[3, 4] were performed by Crafoord in 1944 and Gross in 1945. A large number of operations for this condition have been performed by many surgeons since that time. Although the operation may be technically difficult in some cases, it can be performed by surgeons experienced in vascular surgery with little risk. As yet, follow-up studies of too few patients operated on for coarctation of the aorta have been made over periods sufficiently long to permit accurate evaluation of the benefits of operation, but the results so far have been gratifying. The operation is based on sound physiologic principles, and there is every reason to believe that the long-term results in most cases will be excellent.

DIAGNOSIS

None of the clinical symptoms of coarctation of the aorta are of particular significance in making the diagnosis. As a rule, however, the condition is not difficult to diagnose. All that is required in most cases is to keep this condition in mind and to examine the vascular system carefully when carrying out every physical examination. Measurement of blood pressure by the arm-cuff method should be performed routinely even among children. The diagnosis of coarctation of the aorta has been made so infrequently in children that it seems likely that this important test is neglected by many pediatricians. Even a slight elevation of blood pressure should arouse suspicions of its presence. It must be recognized too that this condition can be present in children whose blood pressure determinations are within normal limits. Therefore examination must include a careful palpation of the abdominal aorta and femoral arteries. If pulsation in these vessels is decreased or absent, or if there is a slight delay in the femoral pulsations as compared to the carotid or radial pulse, coarctation should be strongly suspected. Cardiac murmurs are not diagnostic of coarctation of the aorta, but usually a loud systolic murmur, heard best at the level of the fifth rib posteriorly, is present, and often a

murmur occurs which is suggestive of aortic regurgitation and is heard best over the aortic area anteriorly.

Careful examination for evidence of collateral circulation should be carried out for patients suspected of having coarctation of the aorta. The condition produces a remarkable example of collateral circulation, most pronounced in the scapular areas posteriorly. *The clinical and physical manifestations of coarctation of the aorta are less marked and more difficult to discover in infants and children than in young adults.* Evidence, however, can be detected by an alert pediatrician. According to Griffith,[5] it is a common cause of heart failure in infants. Bahn, Edwards and

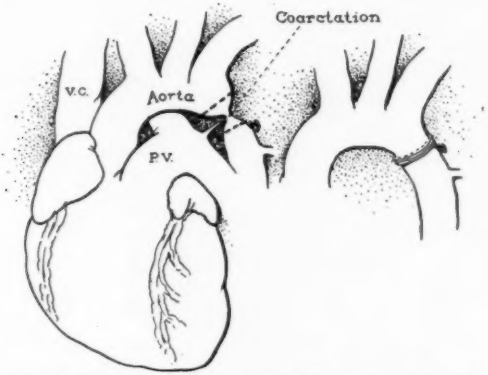

Fig. 57. Diagrammatic representation of a coarctation and end-to-end reconstruction of the aorta.

DuShane[6] recently reported that necropsy revealed coarctation of the aorta to be responsible for the deaths of three infants who had died of heart failure of unknown etiology. Coarctation of the aorta also was discovered to be the cause of heart failure in a ten week old infant seen at the Mayo Clinic. Operation for relief of the coarctation was performed successfully (Fig. 57).

Roentgenographic evidence of coarctation of the aorta may be practically pathognomonic or almost absent. When present, the usual findings are rounding of the cardiac apex, left ventricular enlargement and a narrow mediastinal shadow with a decreased or absent aortic knob (Fig. 58). Notching of the inferior margins of the ribs due to erosion by dilated tortuous intercostal arteries is diagnostic. The absence of notching does not, however, rule out the presence of coarctation of the aorta. Notching of the ribs has been noted in patients only five years of age, but less than half of our patients, most of them young adults, had any roentgenographic evidence of notched ribs. A definite indentation in the aortic shadow at

the site of stricture may be noted roentgenographically in some cases of coarctation, but this finding is not constant in the usual roentgenograms of the thorax.

Electrocardiographic studies may show some changes indicating strain on the left side of the heart, but these studies have not resulted in any findings definitely characteristic of coarctation of the aorta. Ballistocardiography has been advocated as a means of diagnosing the condition, and characteristic wave patterns can be demonstrated by this means. This

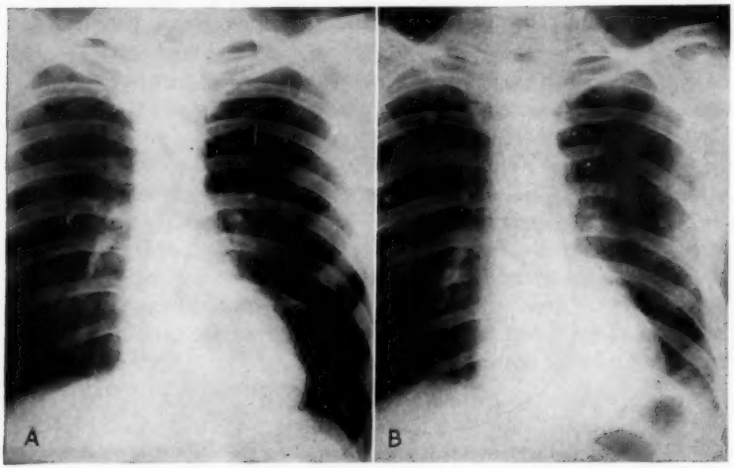

Fig. 58. A, Before operation. Note absence of the aortic knob, enlargement of the left ventricle and notching of the ribs typical of coarctation. *B*, After resection of the coarctation and anastomosis.

test has not been used extensively, however, and is not a necessary diagnostic procedure.

Direct measurement of blood pressure in arteries proximal and distal to the site of aortic obstruction, obtained by inserting needles attached to strain gauge manometers into the radial and femoral arteries, provides a most accurate means of measuring alterations in pressure and flow of blood produced by coarctation of the aorta. This technique has proved useful for research investigations of coarctation of the aorta, but is not necessary for accurate clinical diagnosis.

Angiocardiography and retrograde aortography provide other means of diagnosing and studying coarctation of the aorta and may offer valuable information regarding the exact location of the stricture in relation to the left subclavian artery and the presence or absence of aneurysms near the site of stricture. These, however, are not simple diagnostic procedures and should be used only in carefully selected cases.

MANAGEMENT

That physicians in general and pediatricians in particular have been overlooking the presence of coarctation of the aorta is evidenced by the fact that of 124 patients operated on for this lesion at the Clinic, only 3 were less than nine years of age and only 20 less than fifteen years of age at the time of operation. It is regrettable that only 16 per cent of these

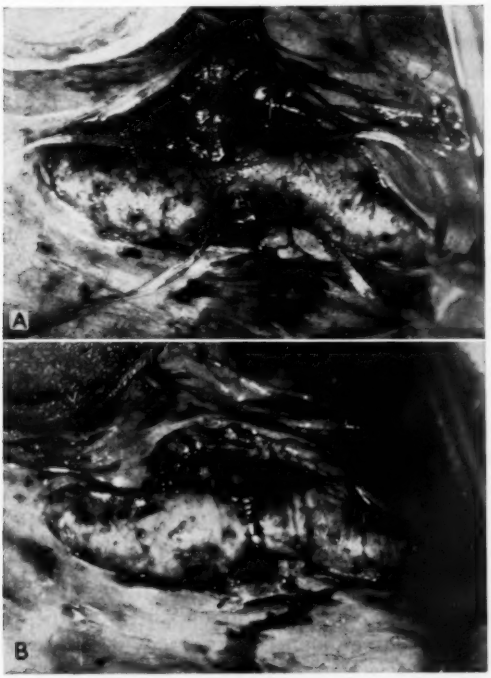

Fig. 59. A, Typical coarctation of the aorta demonstrating the stricture and medial angulation of the aorta due to the ligamentum arteriosum. *B*, Reconsruction of the aorta after resection and end-to-end anastomosis.

patients were operated on at what must be considered the optimal age for operation. Though many patients more than fifteen years of age can be operated on successfully, it is nevertheless true that some irreversible cardiovascular damage is common after that age, and delay in detecting the presence of coarctation may impose severe penalties.

Operation for coarctation can be performed most satisfactorily on patients between three and fifteen years of age. The blood vessels of patients of this age group are elastic and healthy and can be sutured readily. In most cases of coarctation serious damage to the heart and blood

vessels does not develop until after the patient is fifteen years of age. As noted previously, however, serious cardiac enlargement and heart failure may occur occasionally in infants or children as a result of coarctation, and there should be no hesitation in advising operation for such patients, regardless of age. The vascular anastomosis should be made with interrupted silk sutures rather than with continuous silk in infants and children, to avoid interfering with the growth of the vessel at the site of anastomosis.

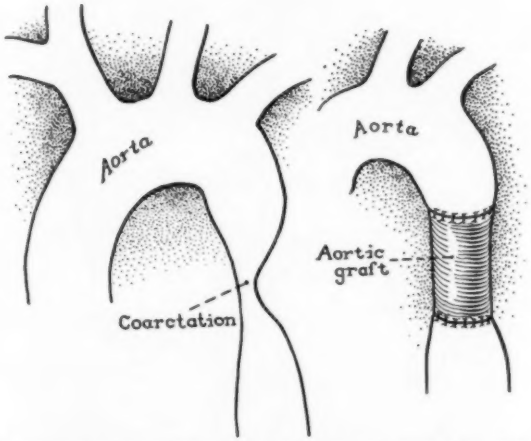

Fig. 60. Diagrammatic representation of a long tapering coarctation of the aorta with reconstruction using an aortic graft.

Other congenital cardiovascular anomalies may coexist with coarctation of the aorta. Bicuspid aortic valves are said to occur in 40 per cent of the patients, and subaortic stenosis and abnormalities of other cardiac valves have been reported. Patent ductus arteriosus occurs somewhat commonly in association with coarctation. In our experience, patent ductus was found in 16 of 124 cases. Patent ductus is usually proximal to the site of aortic stricture, but may be distal as well. We have observed instances of double aortic arch and anomalous origin of the right subclavian artery in conjunction with the condition. The association of other congenital cardiovascular anomalies increases the technical difficulties and risk of operation to some extent, but does not necessarily prevent successful surgical correction of the coarctation.

The development of a surgical procedure for coarctation marks another great step forward in the treatment of congenital cardiovascular lesions. Operations for the relief of coarctation of the aorta can be performed successfully in most instances and with relatively little risk. Seven of the 124 patients in our group died; most of them were older patients with

severe cardiac and vascular damage. If operation can be performed while the patients are young, the risk should be considerably less than 5 per cent.

In the great majority of patients with coarctation of the aorta the narrowed segment of aorta is short. The involved portion can be removed and primary end-to-end anastomosis of the vessel accomplished (Fig. 59). In a few cases, however, the narrowed portion of aorta is so long that it cannot be removed and the aortic lumen reconstructed without the use of a homologous aortic graft. Gross developed and has had extensive experience with the use of such grafts, and there is no question that they can be used to great advantage in some patients having coarctation who could not be treated successfully otherwise (Fig. 60). Aortic grafts, however, should not be used unless absolutely necessary, since long-term results of operation using such grafts have not yet been determined, furthermore, evidence of serious degenerative vascular changes which may have grave consequences has been noted already among some patients having these grafts.

SUMMARY AND CONCLUSIONS

Coarctation of the aorta is not a rare congenital anomaly. It occurs frequently enough that most physicians will have opportunities to see patients with this lesion.

The diagnosis is not difficult in most cases and can usually be made by thorough physical examination of the cardiovascular system without resorting to any laboratory or roentgenologic studies. The most important finding in the physical examination is that of absence of pulsation or decreased pulsation of the abdominal aorta and femoral vessels.

Coarctation may be responsible for cardiac enlargement and heart failure in infants and children.

Most patients having coarctation of the aorta can be treated successfully by surgical operation. The operation carries little risk as compared to the risks associated with an untreated lesion. The optimal time for the patient to undergo operation is before he is fifteen years of age. Early diagnosis of the condition, so that operation can be performed at an opportune time, must be the responsibility of pediatricians.

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ANOMALIES OF THE AORTIC ARCH AND THEIR TREATMENT

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Considering the complicated embryologic development of the great vessels, it is amazing that anomalies of the aortic arch and its branches do not occur more often. When these abnormal vessels cause enough pressure on the esophagus and trachea to give rise to symptoms and signs of obstruction of either or both of these important passageways, a basic understanding of the various vascular anomalies becomes essential for proper diagnosis and treatment. Eighteen patients with constricting vascular rings operated upon at the Children's Memorial Hospital will be discussed.

EMBRYOLOGY AND ANATOMY

The developmental anatomy of the aorta must be reviewed to clarify the types of pressure producing vascular anomalies.[1] During our piscatorial stage of embryonic development six pairs of aortic arches are formed by the joining of the ventral aortic sac and the dorsal aorta to surround the pharyngeal pouch (Fig. 61, *A*). There is one arch for each branchial cleft. The first two arches appear early and disappear promptly. The third aortic arch enters into the development of the carotid arteries. The fourth arch eventually forms the arch of the aorta. The sixth arch produces the pulmonary arteries and ductus arteriosus. The fifth arch makes only a brief appearance and is of no importance. In Figure 61, *B*, the appearance of the aortic arches is outlined as they occur in the 10-mm. embryo. At the 11- to 12-mm. stage the right portion of the sixth arch disappears, while the left remains as the ductus arteriosus.

When the embryo reaches about 15 mm., the right fourth arch disappears between the origin of the subclavian artery and the dorsal aorta,

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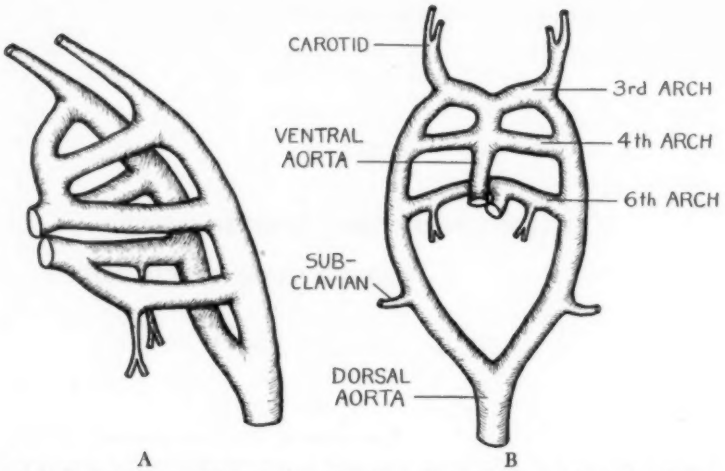


Fig. 61. A, Diagram of lateral view of aortic arches as they pass about the pharyngeal pouch in a 10-mm. embryo. B, Ventral view of aortic arches and important branches.

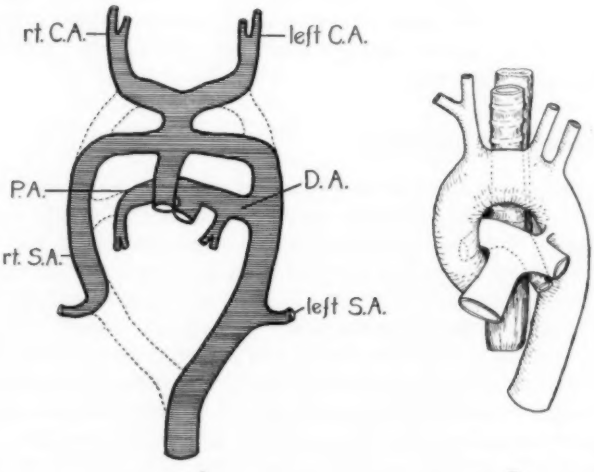


Fig. 62. A, Diagram of aortic arches and branches that persist in normal development. Dotted lines indicate portions of the vessels that disappear. C.A., carotid artery; S.A., subclavian artery; P.A., pulmonary artery; D.A., ductus arteriosus. B, Normal adult configuration of aorta, pulmonary artery, trachea and esophagus.

leaving the normal aortic configuration diagrammed in Figure 62, A. Caudal migration of the heart elongates the carotid arteries, and cranial migration of the subclavian arteries brings the aorta and its branches into their final normal anatomic position (Fig. 62,*B*).

One of the most common variations of this normal development occurs when the aortic arch passes to the right of the trachea and esophagus and descends through the thorax to the right of the midline for at least part of its course. This occurs when the left fourth arch disappears and the right remains (Fig. 63, A). This uncomplicated right aortic arch (Fig. 63, *B*)

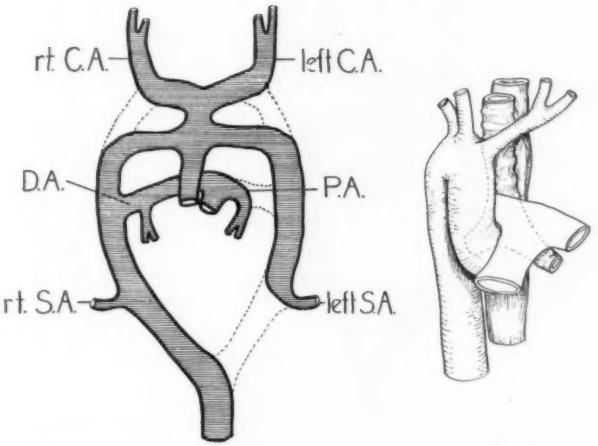
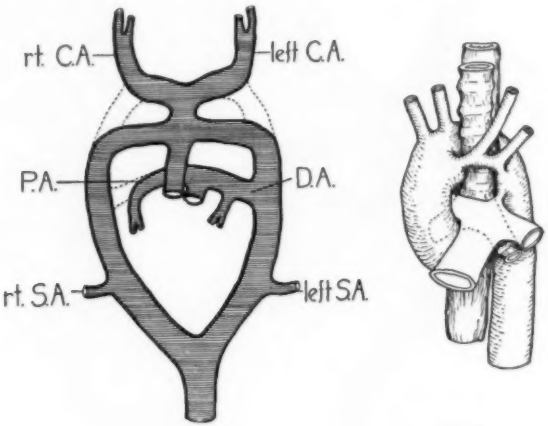


Fig. 63. A, Diagram of vessels that persist in a right aortic arch and descending aorta. Dotted lines indicate portions that disappear. Right dorsal segment of fourth aortic arch remains instead of left. Ductus arteriosus persists on right. *B*, Final appearance of a right aortic arch and right descending aorta.

produces no pressure on either the esophagus or trachea of physiologic importance. Although an esophagram sometimes will show a marked indentation on the right of the esophagus, if there is no other vascular abnormality to complete the encirclement, the esophagus is free to move to the left and no constriction occurs. A right aortic arch is rarely seen in a person with an otherwise normal cardiovascular system. It is seen most often in combination with the tetralogy of Fallot. In approximately 20 per cent of almost 400 patients operated upon for tetralogy the aortic arch passed to the right. The condition is also seen not infrequently with a "vascular ring." We have never observed a right aortic arch in conjunction with the other congenital cardiovascular lesions, such as patent ductus arteriosus, isolated pulmonary stenosis, coarctation or septal defect.

The condition known as "double aortic arch" occurs when both the

right and left dorsal segments of the fourth aortic arch persist (Fig. 64, A). This results in a constricting ring of vessels completely encircling the trachea and esophagus and producing various degrees of obstruction. We have seen this type of vascular ring in 13 operative cases. Five patients had the anterior segment small (Fig. 64, *B*). Five patients had the posterior segment small, so that exposure of the great vessels at operation anteriorly revealed an apparently normal relationship, as in Figure 62, *B*, but posterior dissection revealed a small, short posterior arch (Fig. 65, *A*). In the remaining 3 patients with double aortic arch the aorta arched and de-



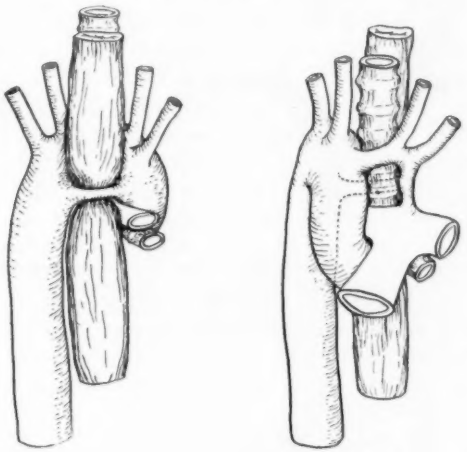
A B

Fig. 64. *A*, Diagram of double aortic arch showing segments which persist. Dotted segments disappear. Note that there is persistence of both left and right dorsal segments of the fourth aortic arch. *B*, Double aortic arch with a small anterior segment showing complete encirclement of trachea and esophagus.

scended on the right. The anterior segment of the double arch arose from the ascending aorta. Giving off the carotid and subclavian artery, it then passed to the left of the trachea and esophagus to be joined by the ductus. The communicating channel then continued posterior to the esophagus to join the aorta descending on the right (Fig. 65, *B*). Because the persistence of both fourth dorsal aortic arches allows for no formation of an innominate artery, the subclavian and carotid arteries have always been seen to arise independently from either the anterior or posterior segment of the double aortic arch.

Another anomaly that may cause compression of the esophagus and trachea is found in a right aortic arch and descending aorta in which an anomalous ligamentum arteriosum and/or an anomalous left subclavian artery coexist. This can be seen diagrammatically in Figure 66, A, where the fourth arch has disappeared on the left between the carotid and

subclavian arteries. This leaves the left subclavian artery originating from the right descending aorta to pass behind and to the left of the esophagus. This alone may be sufficient to cause significant pressure symptoms. If the ductus arteriosus, instead of passing to the right of the trachea, goes around the left to join the descending aorta, an almost complete vascular ring is formed. In two instances we have found a combination of both these anomalies, as seen in Figure 66, *B*.



A B

Fig. 65. A, Posterior view of a double aortic arch with the posterior segment small. *B*, Double aortic arch in which the aorta descends on the right. Dotted lines indicate the posterior segment of the double arch passing behind the esophagus to join the descending aorta and complete the vascular ring.

Another condition that produces an incomplete vascular ring is an anomalous right subclavian artery originating from a normally placed descending aorta. As shown in Figure 67, A, the fourth aortic arch on the right disappears between the carotid and the origin of the subclavian, leaving the right subclavian to originate from the descending aorta below the left subclavian. Figure 67, *B*, shows the oblique course of the right subclavian artery behind the esophagus, causing pressure demonstrable by esophagram and occasionally symptomatic.

In 8 cases of tetralogy of Fallot undergoing aortic pulmonary anastomoses, dissection of the aorta revealed this type of anomaly. None of these patients had had any dysphagia, though postoperative x-ray examinations revealed a marked posterior indentation of the esophagus. We have encountered only 2 patients with this condition that required surgical correction.

Rarely a slight displacement of the origin of the innominate artery may

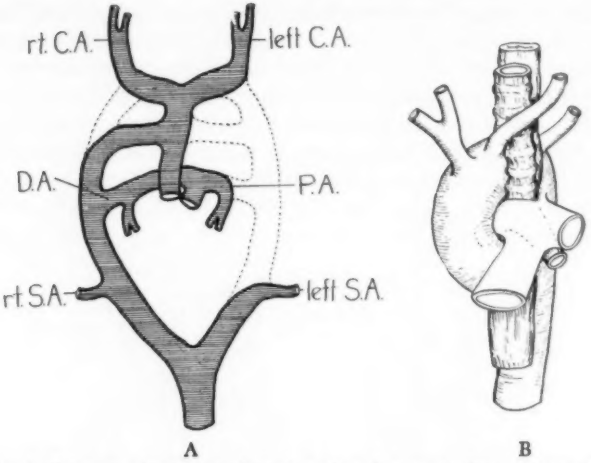


Fig. 66. A, Diagram of portions of aortic arches that persist in a right aortic arch with anomalous left subclavian artery and ductus arteriosus. Dotted segments disappear. B, Combination of right aortic arch and anomalous left subclavian artery and ductus arteriosus. Pulmonary artery attached to the right descending aorta by the ductus completes the constricting ring.

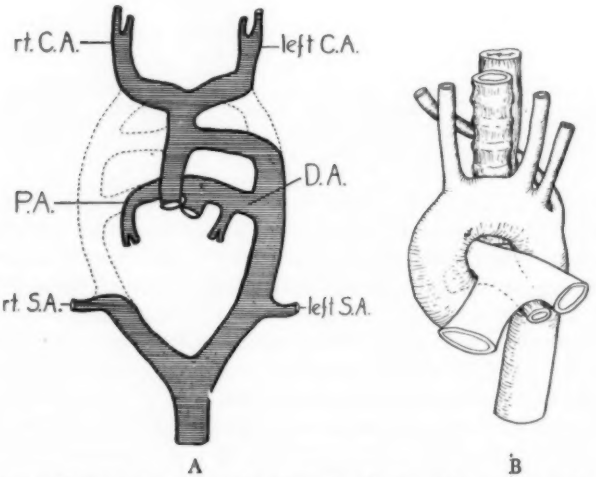


Fig. 67. A, Diagram of portions of aortic arches that persist in an anomalous right subclavian artery. Dotted segments disappear, leaving right subclavian originating caudal to the left subclavian. B, Anomalous right subclavian showing oblique course of the artery as it passes behind the esophagus.

allow the vessel to pass across the anterior surface of the trachea, causing pressure symptoms. One of our patients at operation proved to have the innominate artery arising to the left of its normal position on the aortic arch. Though Gross[2] describes tracheal compression from an anomalous carotid artery, we have not encountered this condition.

DIAGNOSIS

If the vascular ring does not encircle the trachea and esophagus completely or tightly, there may be no symptoms and only minimal findings. The typical case, however, has a striking pattern of symptoms. There is a history of noisy respirations from birth, usually aggravated by respiratory infections and increased during feedings. Pulmonary infections are frequent, and cyanotic attacks occur in some cases. A barking cough usually is noticed by the parents. Symptoms of esophageal compression are not prominent. Less than one third of our patients had such symptoms, ranging from mild dysphagia to vomiting.

More than one third of our series gave a history of having had x-ray therapy for enlarged thymus. Although objective evidence indicates that the thymus plays no role in tracheal compression and sudden death, the myth is so ingrained in the minds of many physicians and most laymen that the doctor feels uneasy if he does not prescribe roentgen therapy when thymic enlargement is noted. More than one half of the infants undergoing cardiac surgery had moderate to marked enlargement of the thymus. These patients had no symptoms of tracheal compression and survived prolonged anesthesia and difficult surgery just as well as the patients with a normal or small thymus.

Naturally, x-ray therapy has not relieved the symptoms of compression of the trachea by a vascular ring, but has served only to delay proper diagnostic procedures and treatment.

Physical examination usually reveals a patient with respiratory difficulties, as evidenced by inspiratory and sometimes expiratory stridor of a crowing or wheezing nature. Flexion of the neck usually causes increased respiratory difficulty. There may be marked inspiratory suprasternal and intercostal retractions increased by excitement and crying. Expiration may be prolonged with evidence of emphysema. These children cough frequently, and the sound has been described variously as "brassy," "barking" or "seal-like." Once heard, it is easily remembered. Cyanosis may be present upon crying or during feedings. True difficulty in swallowing is uncommon.

Loud, coarse ronchi are heard over the lungs on inspiration and expiration, but moist rales are present only when pneumonia or atelectasis is superimposed. Multiple congenital anomalies do not seem to accompany this condition.

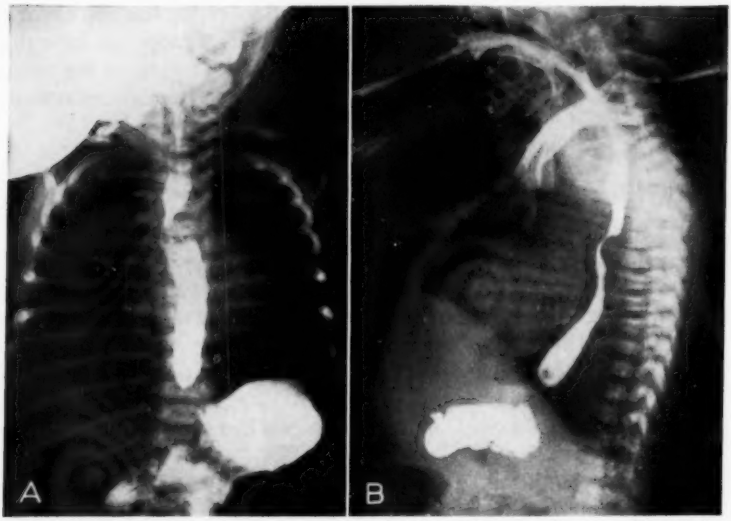


Fig. 68. Esophagram of a patient with a double aortic arch with a small posterior segment. *A*, Anteroposterior view shows notching and constriction of the esophagus at the level of the aortic arch. *B*, Lateral view shows posterior notching of esophagus and constriction of tracheal air column.

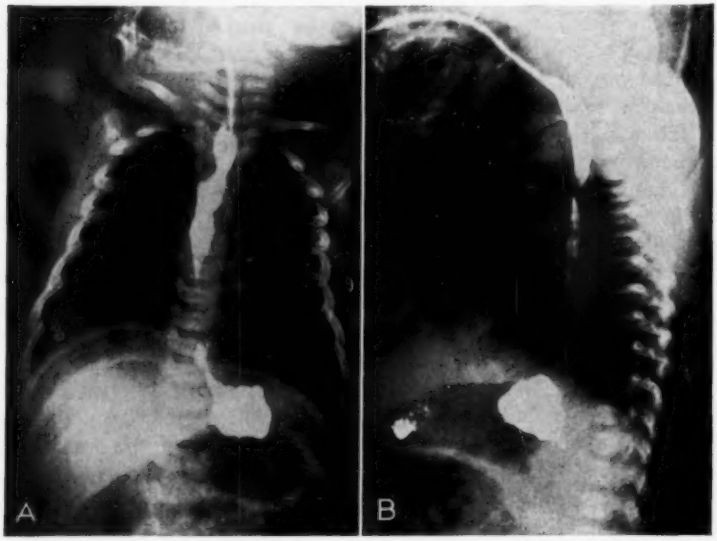


Fig. 69. Esophagram of a patient with a double aortic arch and right descending aorta. *A*, Anteroposterior view shows the larger indentation on the right of the esophagus. *B*, Lateral view shows constriction of esophagus and tracheal air column.

The most important diagnostic procedure is an esophagram with barium or lipiodol and anteroposterior and lateral x-ray pictures of the chest. Frontal views will show a notching of both sides of the esophagus with resulting constriction at the level of the aortic arch. Lateral views show a posterior defect in the esophagus—round, clear-cut and constant, often described as a "cookie bite" out of the esophageal shadow. Figure 68 shows the roentgenograms of a child with a double aortic arch with the

Fig. 70. Esophagrams of a patient with an anomalous right subclavian artery showing an oblique indentation of the esophagus posteriorly.

aorta descending on the left. The large left lateral indentation on the anteroposterior view and the small posterior indentation on the lateral view suggest that the large segment of the double arch is anterior. Another thing noted on lateral view is the fusiform constriction of the air shadow in the trachea at the same level as the esophageal compression. Such x-ray pictures establish the diagnosis of double aortic arch.

Figure 69 shows the roentgenograms of a patient with a double aortic arch associated with a right arch and descending aorta indicated by the large indentation of the esophagus on the right side in the anteropos-

terior view. The lateral view shows the marked constriction of both the esophageal barium column and the tracheal air column. Esophagrams in cases of an aberrant right subclavian artery are diagnostic because of the obliquity of the posterior indentation of the esophagus from left lower to right upper and also the absence of constriction of the tracheal air column (Fig. 70).

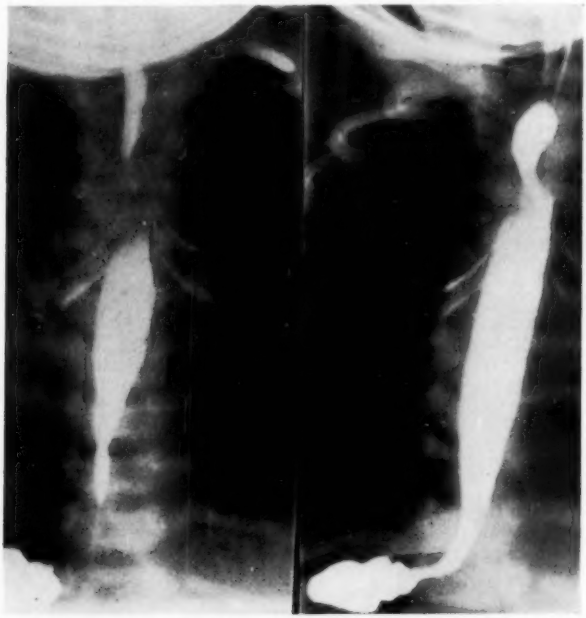


Fig. 71. Esophagram and tracheogram of a patient with a right aortic arch and anomalous left subclavian artery and ductus arteriosus. Esophagus and trachea are constricted at the same level.

We have not found lipiodol tracheograms to add much to our information, and in a few instances injection of the oil caused alarming respiratory difficulties. A combined esophagram and tracheogram is shown in Figure 71, confirming the tracheal compression and outlining its level above the carina. This patient had a right arch and descending aorta with an anomalous patent ductus arteriosus and left subclavian artery.

Laryngoscopy and bronchoscopy are frequently performed mainly to rule out intrinsic obstructing pathology. Tracheal stenosis, web formation tumors, vocal cord pathology, inflammatory edema, and the like, can be eliminated from the differential diagnosis by these procedures. Typical findings are a tracheal flattening at the level of the aortic arch apparently

due to extrinsic compression. The bronchoscope can usually be pushed past this obstruction with ease, resulting in improved respirations. Many times a large accumulation of secretions is found below the obstruction.

Esophagoscopy may show a definite pulsation of the esophageal indentation. In patients suspected of having an anomalous right subclavian artery it may be helpful to feel both radial pulses or take bilateral blood pressure readings as the esophagoscope passes the obstruction. Disappearance of the pulse or definite drop in blood pressure on the right would be diagnostic of this anomaly.

In several patients bronchoscopy and esophagoscopy were not attempted, owing to the severity of the tracheal constriction. If even a mild edema should follow the procedure, the obstruction might become complete. Fortunately, in this type of case, the x-ray findings are usually so outstanding that no other diagnostic tests are necessary.

Other causes for extrinsic tracheal compression, such as mediastinal tumors, must be ruled out by careful examination of the x-ray pictures.

PROGNOSIS

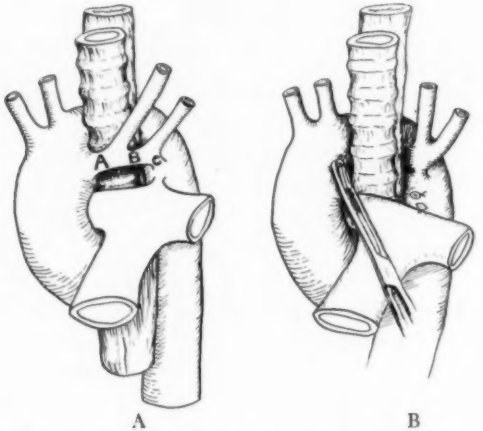
Though it has been suggested that most patients with vascular rings will outgrow their condition, almost all the true double aortic arches we have encountered presented alarming pictures of high grade obstruction to the trachea during the first weeks or months of life, and the patients undoubtedly would not have survived without operation. Naturally, if symptoms are minimal and examinations reveal only a mild constriction, there is no urgent need for operative intervention. As mentioned before, many incomplete vascular rings such as anomalous subclavian arteries never require operation.

One patient not included in this series was a 45 year old housewife operated upon 2 years ago at the Grant Hospital. Symptoms of dysphagia had been present as long as she could remember, and, in childhood, she had learned to overcome the difficulty partially by chewing her food extremely well and washing it down with copious amounts of fluids. Dysphagia progressively increased after the age of 40 until she sought relief. X-ray examinations showed a right arch and vascular ring. Esophagoscopy showed edema and chronic inflammation at the point of esophageal compression. At operation a right aortic arch with an anomalous left subclavian artery and ligamentum arteriosum was found and corrected with complete relief of symptoms. Evidently, chronic irritation had increased the obstruction to a point at which it could no longer be tolerated. Thus even patients with mild disability must be followed carefully and may eventually require surgical intervention.

TREATMENT

With the improvements in anesthesia and the development of thoracic and vascular surgery, direct attack on the constricting vascular ring has become possible. In 1945 Gross[3] reported the first successful surgical correction of this anomaly.

Preoperative care is aimed at decreasing the respiratory difficulty and preventing or treating pulmonary infection. The first objective is accomplished by oxygen therapy and increased humidity. Feedings are given slowly in small amounts, increasing the frequency to maintain an adequate intake. Antibiotics are given prophylactically. If pulmonary infection is present, proper measures for its control are carried out and operation is deferred until all evidence of this complication is gone.



A B

Fig. 72. *A*, Double aortic arch with small anterior segment. Letters indicate possible points of division of the ring: *A*, ideal point of division to give best relief of compression of trachea; *B*, less ideal point of division, since the carotid artery may still press on trachea; *C*, poorest point of division, since carotid and subclavian arteries will still compress the trachea. *B*, Division of double aortic arch. A pair of arterial forceps have been applied at point *A* and the vessel divided. The left-hand stump has been sutured with 5-0 silk, the arterial forceps removed and the vessels allowed to retract laterally. The right-hand stump is ready to be sutured. The ligamentum arteriosum had been ligated and divided. Occasionally the ductus may be patent.

Anesthesia may be one of the greatest stumbling blocks in the way of successful surgical treatment. In a small infant with severe tracheal compression, endotracheal intubation and maintenance of an adequate airway assume more importance than the operative procedure itself. In some instances it has been impossible to pass the endotracheal tube beyond the level of the marked compression of the trachea near the carina. This has led to great difficulties for the patient, anesthetist and surgeon. Cyclopropane, ether and oxygen anesthesia has been used in all cases. Appropriate amounts of scopolamine are given preoperatively, to which morphine is added in the older patients.

The operative approach is through a curved, left submammary incision, cutting the second and third costal cartilages near the sternum and carry-

ing the incision laterally through the third intercostal space. To facilitate exposure, a majority of the thymus is always removed, and the aortic arch and its branches are carefully dissected out until the lesion is exposed. In cases of a double aortic arch with a small posterior segment the proper procedure is undisputed: the arch and descending aorta must be rolled forward, exposing the posterior segment, which is divided between ligatures.

When the anterior segment of the double arch is small, the problem of where to divide the encircling ring arises. Since relief of tracheal compression is the primary objective, division between the ascending aorta and left carotid at point A (Fig. 72, A) would seem to open the ring most completely.

The first thing to be proved is whether the channel between the origin of the left carotid artery and the descending aorta is sufficiently patent to provide adequate blood supply. Temporary compression with a Potts ductus forceps at point A while the anesthetist palpates the temporal or carotid pulse will settle this question. Since the distance between the ascending aorta and left carotid artery may be short, we have found it wise to apply two multitoothed arterial forceps to the segment to be divided, and then cut in between them in the same manner a short ductus arteriosus is divided. The stumps are then sutured with 5-0 silk, as shown in Figure 72, *B*. The carotid and subclavian arteries can spring to the left, relieving the tracheal compression.

If insufficient blood passes through the anterior segment from the descending aorta to the carotid artery, this vessel must maintain its communication with the ascending aorta, forcing the surgeon to divide the ring at point *B* (Fig. 72, A). Since the carotid artery will still lie across the trachea and in many instances cause compression, some type of anterior suspension must be utilized. Interrupted silk sutures through the adventitial layer of the vessel, bringing it forward to the under surface of the sternum, are fairly effective. The subclavian artery and ligamentum arteriosum are divided and allowed to retract.

In one case division was accomplished at point *C* (Fig. 72, A), after which the left subclavian and carotid arteries still were drawn tightly across the trachea. Anterior fixation was attempted, but the postoperative results were poor.

In cases of double aortic arch and right descending aorta the anterior segment is always small and becomes more narrow and inaccessible as it passes behind the esophagus to join the right descending aorta. To preserve the blood supply to the left carotid, division of the ring must usually be done at point *B* (Fig. 72, A). The subclavian artery, ligamentum arteriosum and posterior segment of the double arch must be ligated and divided so that they can retract and relieve the compression. If the carotid artery still causes pressure, anterior suspension may be necessary.

The anomalous right innominate artery originating to the left of the trachea and passing across it, causing compression, can be treated only by anterior suspension.

In the case of an anomalous right subclavian artery passing behind the esophagus, the descending aorta must be approached laterally. The offending artery will be found originating just caudal to the left subclavian. Dissection of the vessel is carried well upwards and behind the esophagus, and ligatures are placed near the descending aorta and as far distally as possible so that a fair-sized segment of the artery lying behind the esophagus can be excised to insure immediate relief of the compression.

The chest is closed in layers, leaving a catheter in the fifth intercostal space at the midaxillary line for closed chest drainage. Postoperatively, the patient is returned to oxygen and humidity and is continued on antibiotics.

Not only must the vascular ring be divided, but so must all constricting fibrous tissue that might continue the compression. To be sure that the operation is to be effective, it is well to free the trachea completely anteriorly and on both sides from the carina to as high in the neck as possible.

Results

Eighteen patients ranging from two weeks to eight years of age have been operated upon at the Children's Memorial Hospital for these types of vascular anomaly during the past six years, including the 2 cases previously reported.[4] There have been five deaths, all in patients with tight double aortic arches. One child died of uncontrollable operative hemorrhage. Another suffered subglottic edema after operation requiring a tracheotomy and died of complication of the latter procedure. Another infant had a double arch with the posterior segment small. This was not recognized at operation, since at that time the entity had not been described. The operation was terminated without relief of the constriction, and the patient died four days later. The remaining 2 patients presented extreme difficulties to the anesthetist in maintaining an adequate airway and died a short time after termination of the operation as a result of anoxia.

In the 13 surviving patients, only one result can be called poor, and that in an eight year old boy who had division of the double arch at point C. All the remaining double aortic arch patients have had good results. One patient with an aberrant right subclavian artery division has had only fair results. The 2 patients with incomplete vascular rings with a right aortic arch can also be classified as having fair results.

Moderate improvement can be expected immediately, manifested by quiet breathing and lack of retraction while the patient is at rest. Inspira-

tory stridor during excitement and the barking cough may persist for many months, but can be expected to disappear gradually. Since the vascular compression has been present during formation of the cartilaginous support of the trachea, we cannot anticipate complete relief of symptoms, but must await return of the tracheal rings to their normal configuration during subsequent growth.

SUMMARY

1. The developmental anatomy of pressure-producing vascular anomalies of the aorta and its branches is reviewed.

2. Observations concerning diagnosis and treatment in 18 cases operated upon for these types of anomalies are presented.

3. Any infant with symptoms of partial obstruction of the airway and dysphagia must be studied with these vascular anomalies in mind.

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SURGICAL TREATMENT OF CONGENITAL CARDIOVASCULAR ANOMALIES ACCOMPANIED BY CYANOSIS

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Surgery for congenital heart disease associated with cyanosis is undertaken only after careful study of the patient. The history, physical findings, laboratory, x-ray and cardiophysiologic findings are discussed, and diagnosis is agreed upon by the cardiologist, cardiophysiologist and surgeon. The anesthetist, an equally important member of the team, reviews the patient's anesthetic needs and best methods for maintaining an efficient open airway.

INDICATIONS FOR OPERATION

An avascular lung associated with cardiac embarrassment and cyanosis, as seen in pulmonary valvular stenosis with either atrial or ventricular septal defect and the various modifications, makes up the majority of lesions in patients with congenital heart disease with cyanosis that can be benefited by surgery.

In the past two to three years the indications for exploration of the chest and pericardial cavities in patients with uncertain findings have been more frequent and at times rewarding. We believe that if there is a chance to benefit the very ill patient with congenital heart disease, the opportunity should be given. Exploration and its possibilities are explained to the parents, who should be wholeheartedly in favor of the attempt to aid their child.

PREOPERATIVE PREPARATION

The preoperative care is directed at improving the patient's general condition. The markedly cyanotic child with a high hemoglobin requires more fluids than the normal patient. Malnutrition and dehydration frequently have to be overcome by intravenous administration of fluids, electrolytes, vitamins and blood. Oxygen therapy is of help to these difficultly oxygenated children and is administered generously.

The preoperative medication varies little with the anesthetists. The small infant may receive no preoperative medication or a little atropine; the older patients may receive both atropine and morphine. The anesthesia preferred is the ether-oxygen combination. The patient is intubated and carried lightly throughout the operation. As soon as the infant or child is asleep a large cannula, of metal or plastic tubing, is placed in the saphenous vein just above the medial malleolus, and a slow drip of normal salt solution or 5 per cent glucose is started.

Plasma and whole blood must be in the operating room before operation. If the pressure falls without loss of blood, plasma can be used without increasing the cellular elements of a blood stream already overloaded with blood cells. Whole blood is reserved for blood loss. Usually neither is needed, but, if required, the need is urgent and an adequate supply must be available.

In warm or hot weather a cooling mattress or ice bags are used to help maintain the temperature at or a little below normal.

THE SURGICAL OBJECTIVE

The object of the operation for congenital heart disease associated with cyanosis and an avascular lung is to increase the blood supply to the lung fields. This can be done in two ways: (1) direct attack on the pulmonary valve (Brock valvulotomy) so as to increase the outflow from the right ventricle, or (2) the shunt operation, such as the creation of a ductus between the subclavian artery and the pulmonary artery (Blalock-Taussig), or the anastomosis of the aorta to the pulmonary artery (Potts-Smith). The direct attack on the valvular stenosis is the surgical procedure of choice whenever possible, and valvulotomy is the only procedure of benefit for isolated pulmonary valvular stenosis with or without an atrial septal defect. The shunt operation is indicated in pulmonary valvular stenosis with a marked infundibular stenosis, small pulmonary artery and a ventricular septal defect. The shunt operation is the only procedure to benefit the patient with tricuspid atresia.

If the preoperative diagnosis leads one to believe that there is a pulmonary valvular stenosis with a poststenotic dilatation of the pulmonary artery, the left chest is opened through the fourth interspace anterolater-

ally, the patient being flat on his back. The fourth and fifth costal cartilages are divided anteriorly, allowing for adequate exposure for a valvulotomy; if an aorta-pulmonary artery anastomosis is deemed advisible, the patient can be turned with his left side up and the incision enlarged.

We have used the Potts-Smith procedure with success in the small infant with tricuspid artesia and tetralogy of Fallot. The Blalock procedure is of benefit and more easily used in patients beyond four to five years of age. The left chest is entered laterally through the fourth interspace for both procedures. The exceptions to these approaches will be considered when discussing the associated anomaly of a right aortic arch, which is found in about 20 per cent of this cyanotic group.

EXPLORATION OF PLEURAL AND PERICARDIAL CAVITIES

A generous incision in the left fourth interspace and gentle, gradual retraction of the ribs will allow for an exposure and work space adequate for careful anatomic inspection, disection and surgical correction. The left pulmonary artery is observed for size and pressure. Usually it is of fair size with low pressure and is easily compressible. At times, however, no pulmonary artery, or just a fibrous cord, will be found which precludes any shunt procedure. The aorta is palpated, and its location, shape and size are noted. We believe that all patients with these congenital anomalies should be given the benefit of an intrapericardial exploration. In spite of the excellent and, in most cases, correct preoperative diagnosis by our co-workers, our team realizes that direct vision of the heart has added greatly in understanding and treating the pathology. Intrapericardial exploration is far from perfect, but with inspection, gentle palpation and pressure studies of the right ventricle, infundibular regions and pulmonary artery the pathology can be more clearly demonstrated and the treatment more intelligently instituted.

Closure of the Chest Wound; Chest Drainage

The pericardium is closed loosely with fine interrupted silk. The chest is drained, using a Pesser catheter from the posterolateral region of the pleural cavity. The lung is well inflated and the chest wound is closed in layers, using fine catgut subcutaneously and silk for the skin. The Pesser catheter is attached to a one-bottle water-seal drainage system. The catheter is removed usually twenty-four to thirty-six hours after operation if, clinically and roentgenographically, the chest shows no intrapleural fluid, and if there is a good expansion of the lung. Aspiration of the chest has rarely been required, and no intrapleural or intrapericardial suppurative processes have been encountered to date.

ANOMALIES WITH DECREASED PULMONARY BLOOD FLOW

Pulmonary Stenosis with Cyanosis

Isolated pulmonary valvular stenosis (without septal defects) is not associated with cyanosis. Suffice it to say that this congenital lesion is satisfactorily diagnosed and responds well to pulmonary valvulotomy (Brock), which is the surgical procedure indicated.

Pulmonary Valvular Stenosis with either Reopening of the Foramen Ovale or Arterial Septal Defect

Increased right atrial pressure secondary to isolated pulmonary valvular stenosis may give rise to the reopening of the foramen ovale, resulting in a

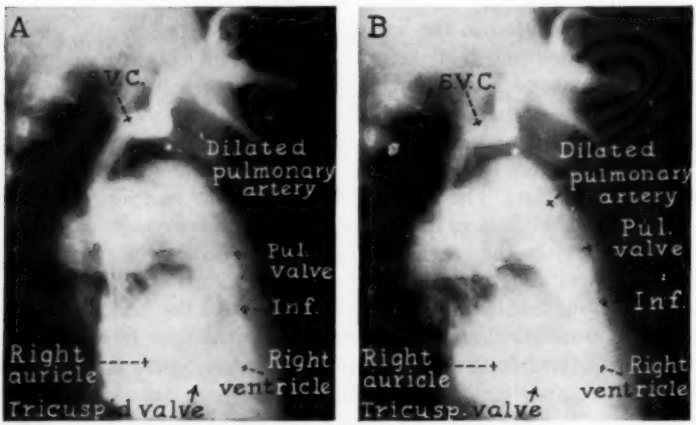


Fig. 73. Angiocardiographs taken at a one-half second interval. Note the infundibular region (*Inf*); in *A* it appears narrowed; in *B* it shows a wide channel. This patient clinically and by cardiac catheterization had an isolated pulmonary stenosis which was benefited by valvulotomy. The importance of a number of films rapidly taken is well demonstrated. The poststenotic dilatation of the pulmonary artery is well shown.

right-to-left shunt of blood and thus a mixing of venous and arterial blood, and cyanosis. The degree of cyanosis varies, depending upon the severity of the pulmonary stenosis and the size of the atrial septal defect. This diagnosis is considered when an enlarged right ventricle and poststenotic pulmonary artery are associated with the atrial shunt. Cardiac catheterization and angiograms are of great help in the preoperative studies (Fig. 73). The only surgical procedure indicated is pulmonary valvulotomy. The creation of an artificial ductus increases the burden to the heart and usually results in cardiac failure and death.

Cases have been reported in which an infundibular stenosis was asso-

ciated with pulmonary valvular stenosis and an atrial septal defect. When the pericardium is opened widely for exploration, a differential diagnosis can usually be made. The smooth, bulging, tense right ventricle and infundibulum, and the markedly dilated, soft pulmonary artery distal to the stenotic valve are noted in patients with a stenosed pulmonary valve as the only obstruction to the outflow tract of the right ventricle. The valve can easily be palpated through the pulmonary artery, and the fine, forceful, jetlike stream of blood is felt as it passes through the stenosed valve and strikes the dilated artery. Careful inspection of the

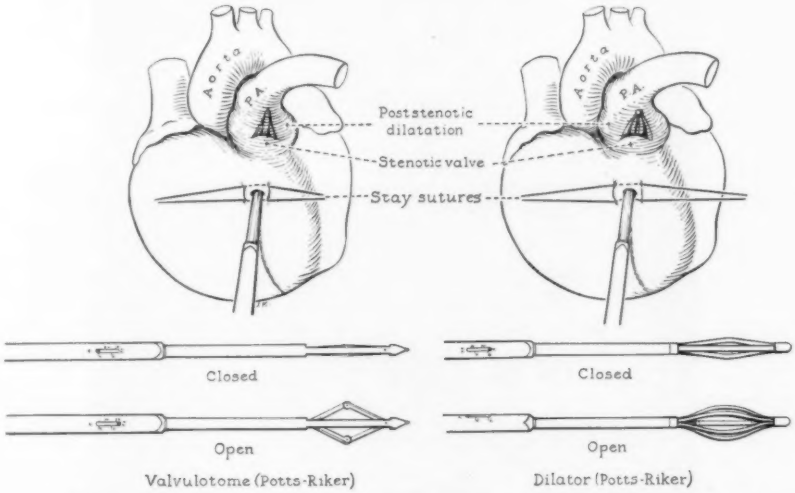


Fig. 74. Modified Brock valvulotomy. Procedures and instruments for incision and dilatation of a stenosed pulmonary valve, as carried out for the correction of isolated pulmonary stenosis, a pulmonary stenosis with an interauricular septal defect and occasionally in patients with a tetralogy of Fallot with a pulmonary valvular stenosis.

outflow tract of the right ventricle may show a slight, narrow line of constriction 1 to 3 cm. from the pulmonary valve. A thrill may be felt at this point which is distinctly different from that just distal to the stenosed pulmonary valve. Pressure readings in the right ventricle, distal to the constriction in the outflow tract and in the pulmonary artery, will usually show marked changes at the three levels, indicating two levels of partial obstruction. This infundibular stenosis may be one of several valvelike stenoses and will yield to incision and dilatation.

Valvulotomy for Pulmonary Valvular Stenosis. The left chest is entered through the fourth interspace anterolaterally. The fourth and fifth costal cartilages are divided near their sternal insertions. The pericardium is opened widely, and careful inspection of the outflow tract and pressure

readings are made to confirm a high pressure in the right ventricle up to the stenotic pulmonary valve. Three to 4 cc. of 1 per cent procaine are injected into an avascular area in the outflow tract of the right ventricle, about 3 to 4 cm. proximal to the pulmonary valve. Two stay sutures of

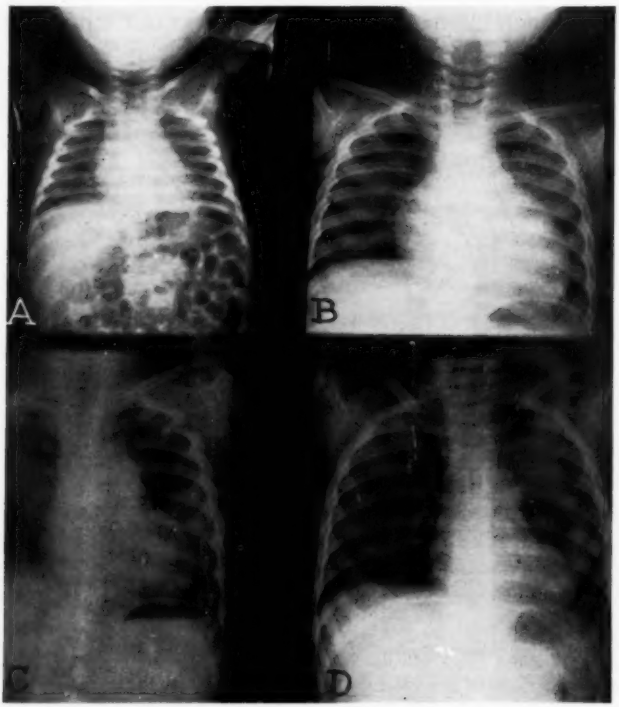


Fig. 75. Chest roentgenograms of a patient with pulmonary valvular stenosis and interatrial septal defect. *A*, The patient is 1 week of age; the heart is slightly large and the lung fields avascular. *B*, The patient is 14 months of age, cyanotic and dyspneic, and the roentgenogram shows an avascular lung and huge heart. *C*, Roentgenogram one month after valvulotomy shows the vascularity of the lungs increased and heart size much smaller. The child's color is normal, and she is active at this time. *D*, Roentgenogram 3 months after valvulotomy shows the heart nearing a normal size, as also are the vascular markings. The child clinically is normal except for a coarse systolic murmur in the pulmonary area.

silk are placed about 0.5 cm. apart at this site. A small incision is made into the myocardium so as to allow a Potts-Riker valvulotome to be inserted (Fig. 74). The index finger and thumb of the left hand palpate the instrument as it passes into the pulmonary artery and make sure that the valvulotome is not opened to such a degree as to injure the vessel wall. The valve is incised in the horizontal plane and then dilated, using

the Potts-Riker dilator at the site of constriction. The instrument, as it dilates, can be felt by the left index finger and thumb. The valve may be thin and easily incised and dilated, but a thick, firm stenotic valve may require repeated, gradual dilatations to obtain an adequate opening. The incision in the myocardium is closed with two or three interrupted silk sutures superficially placed.

The immediate reaction is usually one of improved color, diminished right ventricular pressure (as yet we have not obtained a normal pressure)

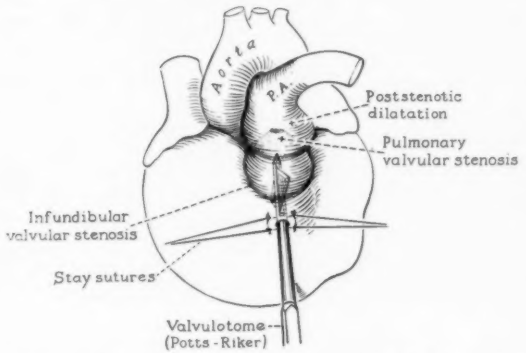


Fig. 76. Valvulotomy for pulmonary valvular stenosis and infundibular valvelike stenosis. The drawing shows a bulging right ventricle and an area of constriction in the infundibular region, beyond which the infundibulum bulges and is tense up to the stenosed pulmonary valve. When pressure studies are made in the right ventricle, distal to the constriction in the outflow tract, and in the pulmonary artery, lower readings will be found distal to the constriction in the infundibulum and in the pulmonary artery. Thus 2 areas of partial obstruction are present, and the infundibular stenosis may be one of several valvelike stenoses relieved by incision and dilatation. The valvulotome enters the right auricle proximal to the infundibular stenosis, incises the constriction in line with the anterior wall of the ventricle, and then passes up to incise the stenosed pulmonary valve in the horizontal plane. The dilator is used in both stenosed areas.

and an increased pulmonary artery pressure. The thrill in the pulmonary artery that was very fine and resulted from a forceful jet of blood coming through a small opening is changed to a coarse thrill, and an increased flow of blood is noted. The favorable signs may not be immediate because of the drop in blood pressure that is frequently associated with intracardiac manipulation and blood loss. With gentleness and replacement of the blood loss the reactions will rapidly be evident.

To date 17 patients with either isolated pulmonary stenosis or pulmonary stenosis associated with an atrial septal defect have been operated upon with no deaths (Fig. 75).

One patient required reoperation 1½ years after the first valvulotomy because of recurrence of symptoms and the finding of pulmonary valvular stenosis. On catheter-

ization the right ventricular systolic pressure was 185 mm. of mercury. The surgical approach was made difficult because of adhesions, but a satisfactory exposure was accomplished by dividing the sternum transversely in line with the fourth interspace. The stenosis had recurred, and a satisfactory valvulotomy and dilatation were completed with immediate and continued improvement.

We believe that the modified Brock valvulotomy is a surgical procedure that has well proved its merit and is here to stay for this congenital anomaly.

Treatment of Pulmonary Valvular Stenosis with Poststenotic Dilatation of Pulmonary Artery, Interatrial Septal Defect and Infundibular Valvelike Stenosis. The findings at intrapericardial exploration of an infundibular valvelike stenosis plus a pulmonary valvular stenosis require the surgeon to incise and dilate both stenosed areas. We believe that this can be best done by entering the right ventricle proximal to the infundibulum and incising the infundibular stenosis in a line perpendicular to the anterior wall of the ventricle, then passing through and incising the pulmonary valve in the horizontal plane (Fig. 76). The dilatation of both areas is separately and carefully done. The infundibular stenosis is dilated to 22 mm., the full extent of the dilator. We have reversed the instruments and incised and dilated toward the ventricle, but find this less satisfactory and more traumatic. Manometer studies before and after assist in assessing the benefit of the intracardiac surgery.

Tetralogy of Fallot

The surgeon should know (besides the facts that the patient has cyanosis, an avascular lung and the other usual findings of tetralogy of Fallot) whether or not the aorta is on the left (80 per cent) or on the right (20 per cent), whether the first portion of the pulmonary artery is dilated and whether both branches of the pulmonary artery are visualized by angiocardiography. This latter information cannot always be definite, but, if it is, the surgeon can enter the chest on the side or location most likely to be of benefit to the patient. The object is to increase the blood flow to the lung.

Shunt Operations. The creation of the artificial ductus (Blalock-Taussig or Potts-Smith operations) increases the blood flow by shunting the blood around the stenosed pulmonary valve and is the operation of choice, in our experience, in patients with a tubular type of infundibular stenosis with a stenosed valve and a small first portion of the pulmonary artery. This is the most common type of outflow tract of the right ventricle found in patients with tetralogy of Fallot. An agenesis of the first portion of the pulmonary artery, or atresia of the pulmonary valve with an infundibular stenosis and a small first portion of the pulmonary artery, requires the shunt operation. Intrapericardial exploration in these cases will show a thick outflow tract of the right ventricle which does not bulge or distend

with pressure, as seen in cases with pulmonary valvular stenosis or pulmonary valvular stenosis with an infundibular valvelike stenosis (Fig. 77). A fine thrill can be felt pressing through the infundibular region and

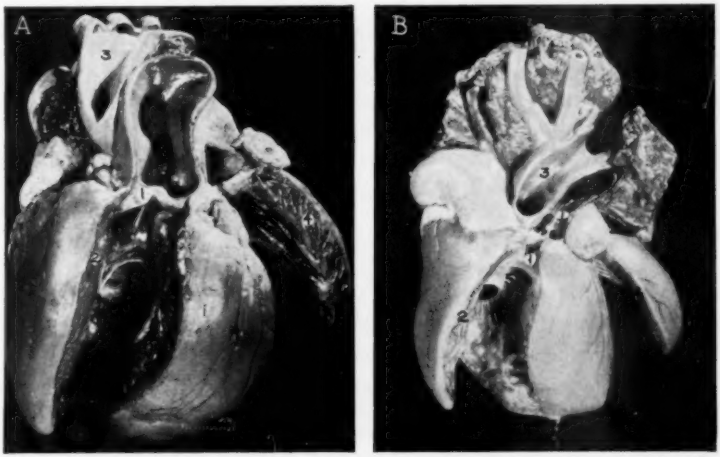


Fig. 77. Photograph of models made from autopsy specimens demonstrating the characteristic differences in appearance and pathology of (*A*) the pulmonary valvular stenosis without infundibular stenosis, and (*B*) the tetralogy of Fallot. The marked infundibular stenosis and thickened, flat infundibulum is compared to the bulging infundibulum in *A*. The poststenotic dilated pulmonary valve in *A* is compared to the small pulmonary artery in *B*. *B* requires a shunt operation and *A* the Brock valvulotomy.

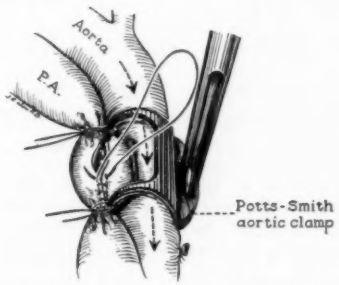


Fig. 78. Pulmonary artery-aorta anastomosis (Potts-Smith). This shunt procedure can be used in small infants with success. The anastomotic opening is made 3 to 4 mm. in length.

reaching its maximum as the blood enters the pulmonary artery. If the valve is closed, no thrill or blood flow will be noted in the first portion of the pulmonary artery. We find that the pulmonary artery-aorta anastomosis is most easily done and is satisfactory in the young patient (Fig. 78). The Blalock operation, or its modifications, is best adapted to

the older child with a subclavian artery of adequate size to anastomose to the pulmonary artery (Fig. 79). Patients with right aortic arches that require the shunt procedures have caused us to modify the Blalock operation most frequently and to realize that the Potts-Smith procedure between the aorta on the right and the right pulmonary artery is in most

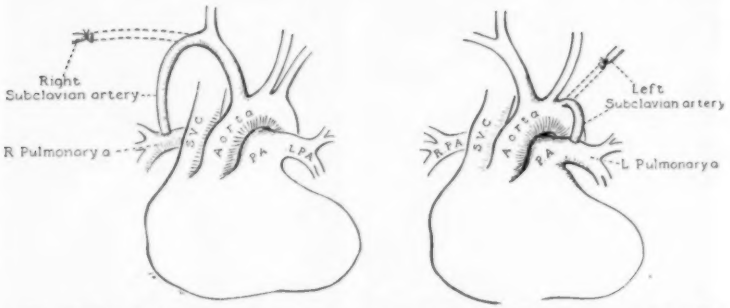


Fig. 79. Subclavian artery-pulmonary artery anastomosis (Blalock), as used for the patient with a tetralogy of Fallot beyond 5 or 6 years of age, having a wide infundibular stenosis. The shunt is usually made on the left side.

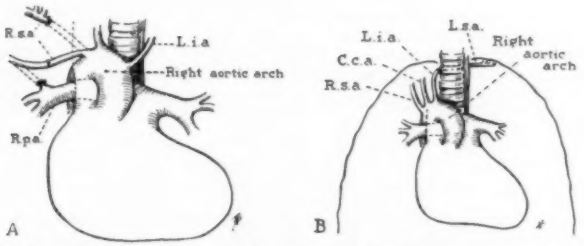


Fig. 80. Two right aortic arch variations. *A*, Shunt operation between a short right subclavian artery and the terminal end of the pulmonary artery as it goes to the upper right lobe. This procedure has given great benefit for 5 years to a onetime wheel chair invalid 13 years of age. *B*, The patient with the anomaly as seen in this illustration received 2 surgical procedures: (1) The left chest was entered with the intent to do a Blalock. No suitable vessel could be found. (2) The right chest was opened 3 months later, and a Blalock operation has given an excellent result.

cases not satisfactory, because the pulmonary artery is at a right angle to the aorta and the resulting anastomosis is of little benefit.

In a very ill infant of 9 months a Potts-Smith operation on the right side gave definite assistance for a year, at which time a Blalock operation on the left side gave dramatic relief. In a patient with a short right subclavian artery an end-to-end anastomosis was necessary between the subclavian and the terminal ends of the pulmonary artery to the upper lobe of the right lung (Fig. 80, A). In a girl thirteen years of age, having a right aortic arch, the left subclavian artery could not be used because it came off on the right side of the mediastinum and passed behind the esophagus at its upper thoracic level (Fig. 80, B). A right-sided subclavian pulmonary artery anas-

tomosis at a later date was satisfactory, and made us realize that the right-side approach for the desperately ill child with a right aortic arch is preferable, because some type of shunt operation can be created. If necessary, a vessel graft can be used to bridge the right pulmonary artery to either the aorta or the subclavian artery.

Valvulotomy. Valvulotomy for tetralogy of Fallot is the procedure of choice when there is a pulmonary valvular stenosis or a pulmonary valvular stenosis with a valvelike stenosis in the infundibular region. We have had experience with 14 such patients, ranging in age from three months to twenty-five years, with encouraging results. The intrapericardial exploration and operation are similar to that for pulmonary stenosis with interauricular septal defect, with or without infundibular valvelike stenosis.

The immediate results of this procedure, clinically, are not as encouraging as those for pulmonary stenosis with an interauricular septal defect. Even though the pressure in the right ventricle is less and that in the pulmonary artery greater, the color of the patient does not improve as rapidly and the patient does not take the procedure as well.

Two deaths have followed this operation, one because we did not recognize the waistlike constriction in the infundibular region, thus not incising and dilating this partially obstructed area, the other due to an atelectasis 6 hours after operation. The remaining 12 patients are benefited, to a greater degree, we believe, than if another abnormality had been added, such as the shunt procedure. Whether or not some of these patients will require reoperation, time will tell. They are being carefully followed. A twenty-five year old, cyanotic man, prior to valvulotomy, had an anemic-appearing lung and normal heart size. After operation his cyanosis was extreme for 2 to 3 days, after which it gradually cleared. Two years later his lung fields are vascular, his heart size is enlarged and his color slightly cyanotic. He is now married and has a job for the first time in his life.

Tricuspid Atresia or Nonfunctioning Right Ventricle

The diagnosis of tricuspid atresia is most often made in an infant with severe cyanosis and oxygen want. In our experience these symptoms occur earlier and are more pronounced in patients with this anomaly than in patients with a tetralogy of Fallot. The child's life depends on an interauricular septal defect and a patent ductus arteriosus or an anomalous vessel supplying blood to the lung. As the ductus closes, the severity of the symptoms and distress increases (Fig. 81). The surgical procedure indicated is the shunt operation; in the very young the pulmonary artery-aorta anastomosis (Potts-Smith) is most beneficial.

Patients ranging in age from 8 days to 3 years have been operated upon for this malformation, and we believe, even though the risk is great (3 operative deaths in twelve), that death would have resulted in the other 9 if the artificial ductus had not been created. The patients are doing well 4 to 5 years after operation, which was done at 8 and 11 weeks of age, when they weighed 7 to 8 pounds (Fig. 82).

In infants the ribs are spread with a mastoid retractor. The pulmonary artery-aorta anastomosis is accomplished between a small soft pulmonary

artery and an aorta the size of a lead pencil. The anastomosis should not exceed 3 to 4 mm.

As in all operative procedures on these very small, ill infants, the anesthetist's job is the most difficult, and he deserves credit for the surgeon's opportunity to create a shunt, and for the crying, kicking, well oxygenated infant that we enjoy seeing, even though the wound has not been completely closed.

Punch Valvulotomy and Infundibular Stenosis

We have had no experience with the punching or reaming out of a channel in hearts with a marked infundibular stenosis. At present we

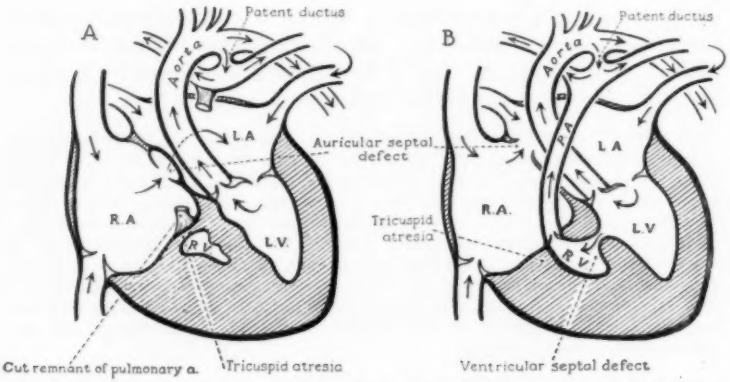


Fig. 81. Tricuspid atresia or nonfunctioning right ventricle. *A*, Completely nonfunctioning right ventricle and pulmonary artery. Life depends on an atrial septal defect and patent ductus. *B*, Interventricular septal defect with a partially functioning pulmonary artery. Life depends on the atrial septal defect and the patency of the ductus. The creation of an artificial ductus is the surgical procedure indicated for this anomaly.

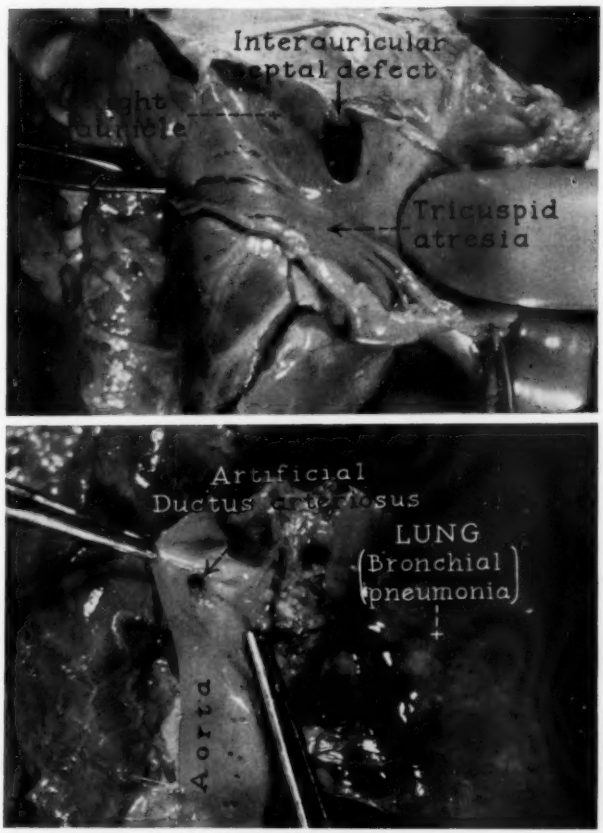
believe that this procedure is too traumatic and dangerous. The shunt operations in time may not be done, and in some clinics they are now considered out of date. We do not agree with this view, specifically as it concerns patients with a tetralogy of Fallot with marked infundibular stenosis. The creation of an artificial ductus gives such good results that we do not feel justified in the more radical procedure, even though, theoretically, it is appealing.

Shunt Operation for Less Common Anomalies

The Blalock and Potts-Smith shunt procedures have benefited patients with pulmonary valvular stenosis and avascular lungs associated with

(1) pseudotruncus, (2) single ventricle, and (3) hearts with both an interatrial and interventricular septal defect. The more anomalies the

A



B

Fig. 82. A, Photograph of autopsy specimen showing the right auricle open, atresia of the valve and a large interauricular septal defect. This infant lived and developed well for 6 months after a pulmonary artery-aorta anastomosis. Death was due to bilateral bronchopneumonia. The shunt functioned well. *B*, Photograph showing the aorta open and the orifice of the shunt patent; the edges smoothly covered with endothelium as seen in a satisfactorily functioning anastomosis.

child has, usually the less benefit is derived from surgery. The additional load of another anomaly is too much for the heart to take, and cardiac failure follows.

ANOMALIES WITH NORMAL OR INCREASED PULMONARY BLOOD FLOW

There remain for discussion the malformations characterized by cyanosis in which, however, obstruction to pulmonary arterial flow is not a feature. They may be grouped together generally as cases wherein desaturated blood reaches the systemic circulation by way of abnormal communications unrelated to obstruction to pulmonary flow; indeed, the pulmonary arterial circulation often may be excessive in both volume and pressure. In general it may be said that this group of anomalies constitutes the "nonsurgical cyanotic cases." It consists of the following: complete transposition of the great vessels, true truncus arteriosus, the Eisenmenger complex, the Taussig-Bing heart, and the single ventricle without pulmonary stenosis. In many instances these may be associated with other defects of circulatory development; consequently this listing does not include all possible situations in which cyanosis is associated with adequate or increased pulmonary arterial flow.

In the group of conditions earlier discussed, efforts at surgically increasing the opportunity for blood to receive oxygen have resulted in clinical improvement and lessening of cyanosis along with its attendant findings. In the conditions now to be discussed, however, the physiologic problem of diminished pulmonary flow is not at hand and proposed surgical attack has not in general been followed by notable success. The occurrence of arterial desaturation is a fault here concerned with an inability of blood, once oxygenated, to find its way unmixed into the systemic circulation.

Complete Transposition of the Great Vessels

Cyanosis and pulmonary vascular congestion are the signs characteristic of this malformation. The only manner in which oxygenated blood may reach the tissues is by virtue of shunts allowing cross mixing between the two circulations prior to ejection through the transposed aorta. Ideally, correction should lie in retransplantation of the great vessels to their expected anatomic locations; as the coronary arteries arise from the systemic trunk, this would entail their partial removal along with the proximal portion of the aorta.

In the absence of a suitable technique for transplantation of the coronaries, it has remained for less ideal methods to be attempted to increase the degree of oxygen saturation in these vital vessels. Admixture between the contents of the two great vessels results in increased oxygen supply to the myocardium, especially if the shunt is in close proximity to the coronary ostia; this was early suggested by Dr. Benjamin M. Gasul for a related condition.

When a large ventricular septal defect accompanies transposition, it has been observed that pulmonary congestion is more marked and that clinically the patient's condition is less acute than in instances unaccom-

panied by the shunt. Nearly all patients surviving for a year or more have been those with ventricular septal patency, the mixing of saturated with unsaturated blood permitting a higher degree of oxygenation in the systemic as well as in the coronary supply.

In those infants with transposition in which a defect in the ventricular septum is not present, life is sustained for a time by admixture through the foramen ovale, auricular septal defects, if present, and patent ductus arteriosus. These patients are deeply cyanotic, present less roentgenographic evidence of adequate pulmonary flow, and are clinically precarious, many surviving for only a brief time. In a few cases of transposition there is a complicating pulmonic stenosis or hypoplasia, and herein the bronchial arteries may constitute the patient's lifeline. Recent evidence indicates that unsaturated systemic blood reaching the lung fields through enlarged bronchial arteries enters the lumina of pulmonary arteries by way of anastomoses with their vasa vasorum.

Surgical retransposition of the vessels, together with closure of existing shunts, will constitute restoration of the circulation to normal. The technical features of such a formidable undertaking have been reflected upon and certain lines of attack have been proposed. Early experimental work is being eagerly observed, but clinical application must be consigned to the future when perfection of pump-oxygenator equipment and other techniques permit deliberate surgery upon the open heart.

The creation of an aortic septal defect, that is, the surgical production of a communication between the aorta and the pulmonary artery in close proximity to the coronary ostia, has been proposed and executed clinically in a few cases. Its ultimate place in the treatment of these extremely precarious patients awaits broader application.

The surgical creation of interventricular septal defect has been difficult of achievement and has not yet become clinically applicable. As was noted earlier, it is patients with large ventricular septal defects who have lived the longest. That this is not adequate compensation for the principal defect, however, is attested by the fact that only a few have been reported to survive to adulthood.

Production of artificial communication between the atria or right atrium and the pulmonary veins has been proposed and carried out in several manners, the most noteworthy being the ingenious technique described by Blalock and Hanlon, in which advantage is taken of the area of adherence between the right pulmonary veins and the posterior surface of the right atrium in creation of a low-pressure shunt. This is augmented by an anastomosis between the right subclavian artery and the right pulmonary artery. Early improvement was noted in some of the cases so treated.

Surgical transposition of the veins entering the heart is subject to technical hazards common to venous anastomoses for other conditions

as well as the anatomic difficulties pursuant to surgical intervention on the posterior of the right and left sides of the heart. Were the venous trunks transposed successfully, the coronary arteries would now receive unsaturated blood.

Taussig-Bing Syndrome

Blalock reports a better postoperative prognosis for patients with transposition of the aorta and a levo-position of the pulmonary artery than for those treated for the typical transposition of the aorta and pulmonary artery.

Truncus Communis

The presence of true truncus arteriosus is not always attended by visible cyanosis, but, because of the blending of unoxygenated blood with the systemic circulation, peripheral desaturation is certain to be present in greater or less degree. The exposure of the pulmonary arterial tree to systemic pressures is likewise a condition of this malformation. Failure of the embryonic conus truncus to undergo its expected spiral division into two trunks may result in one of several anomalous end results, three of which are (1) aortic septal defect, which is a rare lesion not associated with cyanosis; (2) the so-called true truncus, in which the pulmonary arteries arise from the common vessel either bilaterally or posteriorly by way of a short vessel representing a ductus arteriosus; (3) "pseudo-truncus," in which prominence of pulmonic arterial circulation is lacking. This last situation was referred to earlier. In "true" truncus as well as in the minor variations no anatomic rearrangement is presently feasible.

The Eisenmenger Complex

In this disorder again we are dealing with a "nonsurgical" condition, nonsurgical because acceptable attack has not yet been forthcoming. Patients with this defect differ from those with the tetralogy of Fallot only in the absence of obstruction to pulmonary flow; indeed, the pressures on the pulmonary vascular bed are a significant factor leading to death in these cases. Attempts to protect the pulmonary bed have been suggested, and techniques have been devised whereby surgical pulmonary stenosis can be produced. Whereas a measure of protection may be given the pulmonary vascular bed against high pressures, it is not possible by any method now known to achieve the delicate balance between Eisenmenger's and Fallot's conditions optimum for greatest life expectancy. Whether the addition of pulmonary stenosis in these patients, placing an increased burden upon the laboring right ventricle, is to become an acceptable therapeutic measure is open to serious doubt.

Single Ventricle without Pulmonary Stenosis

This malformation may appear in a variety of degrees, as may nearly all congenital malformations. It is not simply a large ventricular septal defect, but rather there are usually two ventricular chambers, one being rudimentary.

In a select few cases of this anomaly a large pulmonary artery transmits the bulk of the flow as well as the major pressure from the larger ejection chamber. These cases may be given some measure of protection by the surgical instillation of pulmonary stenosis, wherein no added work load is presented to the ventricle, but pulmonary tension may be reduced. Limited clinical application seems somewhat encouraging, yet here again we are observing the infancy of surgical remedy for a complex malformation. It has been suggested that should growth of the narrowed pulmonary artery not keep pace with its needs, a shunting procedure may become necessary later in the child's life.

CONCLUSIONS

The surgical treatment of congenital cardiovascular anomalies accompanied by cyanosis has been discussed, particularly in relation to our experiences.

The patient with a congenital heart anomaly associated with cyanosis and an avascular lung can usually be benefited by operation. Patients having similar clinical findings, associated with increased pulmonary blood flow, continue to challenge all workers in this field for new and better surgical procedures. Reports concerning the artificial lung-heart apparatus give encouragement to this latter group, and it is hoped that in the not too distant future a brighter prognosis will be forthcoming.

Limitations of space make it necessary to omit the references here. They will appear, however, in the authors' reprints.

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CARDIAC ARRHYTHMIAS IN INFANTS AND CHILDREN

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From a clinical standpoint three developments stand out in the field of cardiac arrhythmias in infants and children, all pertaining to paroxysmal tachycardia: (*a*) the recognition of paroxysmal tachycardia in early infancy as a clinical entity,[33] (*b*) the recognition of "repetitive paroxysmal tachycardia"[61] as a clinical entity, and (*c*) the recognition of the occurrence and significance of the Wolff-Parkinson-White syndrome[91] in infants and children. This is not the place for an exhaustive presentation of our subject, and only the more common disturbances of formation and conduction of the cardiac impulse will be discussed.

Many of the irregularities of the heart beat can be recognized at the bedside, particularly if we have trained ourselves by correlating the results of the electrocardiographic analysis with the findings on physical examination; nevertheless, electrocardiographic examination should be carried out whenever it is available, since adequate therapy depends entirely on a correct diagnosis of the cardiac disturbance. Some of the principal criteria of electrocardiographic differential diagnosis are pointed out in the legends to Figures 83 to 89.

SINUS TACHYCARDIA, SINUS BRADYCARDIA, SINUS ARRHYTHMIA, WANDERING PACEMAKER

The range of the rate of the normal pacemaker is a wide one; however, such extremes as are illustrated in Figure 83 are exceptional. Whenever

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This department is supported in part by the Michael Reese Research Foundation.

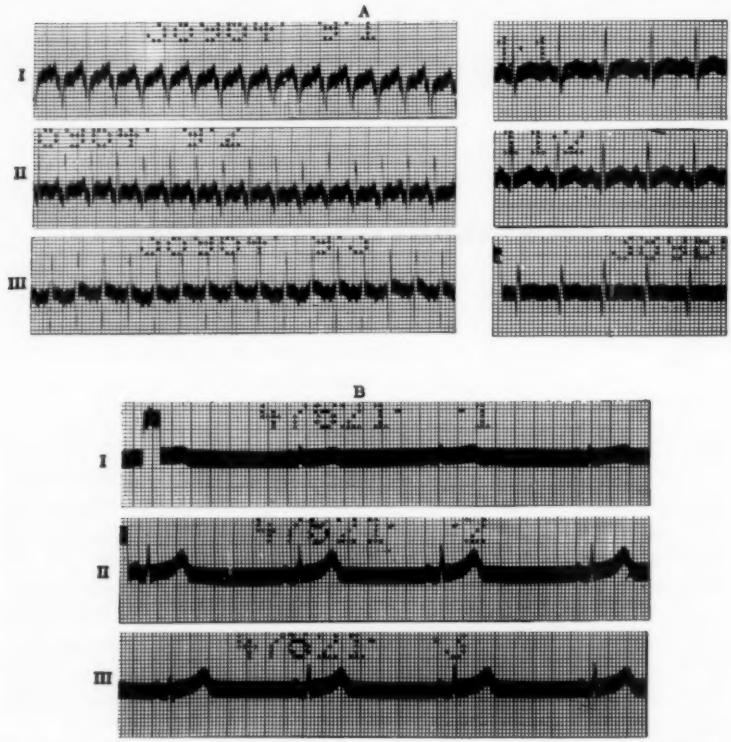

Fig. 83. Extreme (abnormal) rates of the sinus pacemaker in childhood (sinus tachycardia, *A*, and sinus bradycardia, *B*).

A, Tracings obtained in a 3 year old girl with acute pericarditis. At the left the rate is 230 and regular. In the 3 limb leads shown each QRS is preceded at a P-R interval of 0.10 second by upright P waves. The latter are identified to be of sinus origin by comparison with the tracing to the right, taken 2 days later, when the rate had gradually slowed down to 150 and P-R measured 0.12 second. Only in retrospect was it possible to rule out an ectopic auricular tachycardia in the first tracing, since the contour of the P waves was similar on both occasions.

B, Record of a 12 year old psychotic boy in severe inanition. The auricular rate is unusually slow, varying between 38 and 42. P and P-R are of normal contour and duration. There appears, therefore, to be an extreme sinus bradycardia, but the possibility that the sinus rate is actually twice as fast, and there is a persistent 2:1 sino-auricular block, must be considered. Note the absence of escape of a subsidiary (auriculoventricular nodal) pacemaker expected to occur at such slow ventricular rates. This supports the interpretation of sinus bradycardia, with generalized depression of impulse formation in all cardiac pacemakers, as occurs in malnutrition.

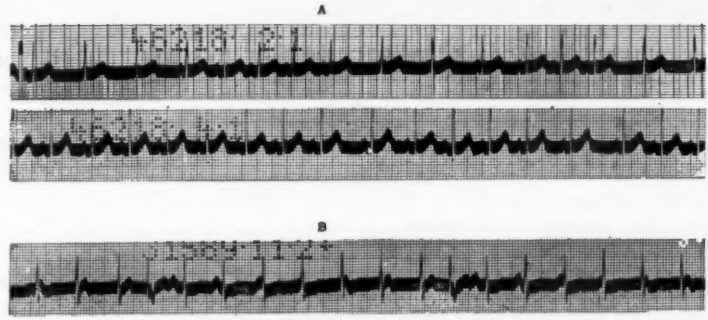

Fig. 84. Intermittent auriculoventricular dissociation (*A*) and incomplete auriculoventricular dissociation with ventricular captures (*B*) due to increased activity of the subsidiary auriculoventricular nodal pacemaker in rheumatic carditis (without evidence of auriculoventricular block).

The upper strip of *A* was obtained in a 3 year old girl with acute rheumatic fever. The auricular rate varies between 75 and 125, owing to a pronounced respiratory sinus arrhythmia. The P-R interval of the conducted sinus beats is normal (0.14 second). During the slower phases the subsidiary auriculoventricular nodal pacemaker escapes the control of the sinus node and interferes with the transmission of the impulses of the latter to the ventricles. The result is intermittent auriculoventricular dissociation. During this phase the ventricles are under the command of the auriculoventricular node discharging at an unusually fast rate of 85, while the auricles are controlled by the slower sinus node.

In the lower strip, obtained 6 days later, a similar sinus arrhythmia is present. Although the sinus rate temporarily slows to 83, no nodal escape takes place this time. The temporary enhancement of the activity of the subsidiary pacemaker, leading to intermittent auriculoventricular dissociation in the first record, can be considered evidence of active involvement of the myocardium by the rheumatic process.

In *B*, obtained in a 12 year old girl with rheumatic heart disease, P waves can be spaced throughout the record at a regular rate of 100, but their position in the ventricular cycle varies from beat to beat. The ventricular rate is faster (107) and regular except for two pairs of beats (the fourth and fifth, and the twelfth and thirteenth) which occur earlier, and are preceded by P waves at P-R intervals measuring 0.28 and 0.20 second respectively. In the major part of the record there is, therefore, auriculoventricular dissociation due to the presence of a fast nodal pacemaker exceeding the rate of the sinus node and interfering with transmission of sinus impulses to the ventricles. None of these nodal impulses is conducted backwards to the auricles. At times, however, two successive sinus impulses reach the auriculoventricular junction when its normal absolute refractory phase after a nodal discharge is over, and succeed in traversing the junction and in activating the ventricles ahead of the next nodal impulse. Such "ventricular captures" are represented by the 2 pairs of earlier ventricular beats. The first of them has a prolonged P-R and a widened QRS (aberrant ventricular conduction), because it occurs earlier in the ventricular cycle, during the relative refractory period of the auriculoventricular junction and of the ventricles. The nodal tachycardia, leading to the incomplete auriculoventricular dissociation, disappeared within a few days and normal sinus rhythm was resumed. It was, as in *A*, considered evidence of activation of the rheumatic process.

In both instances the disturbance of rhythm was the result of 2 factors: (*a*) the enhanced activity of a subsidiary (auriculoventricular nodal) pacemaker and (*b*) the normal refractory period of the auriculoventricular junctional tissues. Such cases must be distinguished from auriculoventricular dissociation due to auriculoventricular block (cf. Fig. 89) which is the result of abnormal prolongation of the refractory period of the auriculoventricular junction.

the ventricular rate determined by auscultation exceeds 180 per minute in a child, or 200 in an infant, an abnormal mechanism should be suspected. A persistent *sinus tachycardia* of 120 to 140 in an older child requires investigation; occasionally no cause can be found, and the tachycardia subsides within a few years without leaving any ill effects.[48] A regular rate slower than 60 in older children and slower than 80 during the first and second years of life suggests the presence of block, usually complete auriculoventricular block (Fig. 89, C) with a subsidiary pacemaker in command of the ventricular action.

Sinus arrhythmia (Fig. 84, A, lower strip) is a physiologic phenomenon more pronounced with slower rates and, therefore, more noticeable in older children. Its absence, particularly with slow rates, tends to substantiate the suspicion of complete auriculoventricular block, easily confirmed by auscultation. Its absence with faster rates may also be a diagnostic clue suggesting an abnormal mechanism, e.g., auricular flutter with persistent 2:1 auriculoventricular conduction. It has been claimed that sinus arrhythmia in infants is independent of respiration;[59] in children over two years of age it is respiratory in nature, and an attempt should be made to elicit it by deep breathing if a slow rate is found and heart block is suspected. On occasion, a sinus arrhythmia may be so irregular that an electrocardiogram is necessary to rule out an abnormal mechanism like frequent premature systoles.

Sinus arrhythmia may be associated with the phenomenon of a *shifting pacemaker*, characterized in the electrocardiogram by a changing shape of the P wave (and varying duration of P-R). It can usually be distinguished from ectopic premature systoles by the gradual transitions of the two rhythms.

AURICULOVENTRICULAR DISSOCIATION WITHOUT BLOCK

Slowing of the sinus rate may give rise to temporary taking over control of the ventricle by a subsidiary (usually auriculoventricular nodal) pacemaker; if this occurs only for occasional beats ("escaped beats") during periods of marked slowing of the irregular sinus pacemaker, it is of no significance; however, *a sinus bradycardia (rate of less than 70 per minute) may occur during active rheumatic fever*[16, 86] *together with an increased irritability of the subsidiary pacemaker which enhances its inherent rate to about 80 per minute.* The increase of the rate of the auriculoventricular nodal pacemaker over that of the sinus pacemaker, and interference of the two impulses in the auriculoventricular junction, are responsible for the appearance of auriculoventricular dissociation without auriculoventricular block, a disturbance without dynamic significance, but of great clinical importance as positive evidence of myocardial involvement.[12, 13, 60, 69, 80, 85] The same disturbance may be seen in other acute infec-

tions,[57, 76] but is particularly significant for the diagnosis of active rheumatic carditis.

The diagnosis can be suspected at the bedside if auscultation reveals marked variations in the intensity of the first heart sound indicative of auriculoventricular dissociation, a regular ventricular rate over 80, and occasional "premature beats" caused by "ventricular captures." Two examples of such a disturbance are illustrated in Figure 84. However, on occasion first degree auriculoventricular block may be present and facilitate the appearance of incomplete or complete auriculoventricular dissociation due to rapid discharge of an auriculoventricular nodal pacemaker.

PREMATURE SYSTOLES

Premature systoles, common in the adult, are rare in children[70] (except for those induced mechanically during cardiac catheterization or surgery). They were reported to occur more frequently in the newborn and in premature infants,[65] but this observation was not confirmed by subsequent studies.[41, 47] Premature systoles of ventricular origin occur more often than those of auricular or auriculoventricular nodal origin, but any variety can be observed more often in the presence of organic heart disease than in its absence. Premature systoles tend to disappear with higher rates and probably for that reason are seen less often in infants than in older children. An instance of ventricular premature beats during sinus tachycardia is illustrated in Figure 85, *B*.

A patient with premature systoles should undergo a thorough examination; if no evidence of organic heart disease or an acute infectious process is found, no further clinical significance need be attached to the presence of premature systoles, since there is no evidence that such an irregularity has any influence on cardiac function or development of the child.[47] Premature systoles occurring in acute infectious diseases may point to cardiac involvement; in acute rheumatic fever, but more often in advanced rheumatic heart disease with mitral valve involvement, frequent auricular premature systoles may occur from several foci with variable ventricular response (Fig. 85, *A*). They may herald the onset of auricular fibrillation, which then can be prevented or delayed by quinidine therapy. Ventricular premature systoles appearing during digitalis treatment usually indicate digitalis toxicity and hence are an important sign for its discontinuance (Fig. 86, *B*).

AURICULAR FIBRILLATION AND FLUTTER

In the great majority of children *auricular fibrillation* is a consequence of rheumatic heart disease and is most commonly seen in cases of ad-

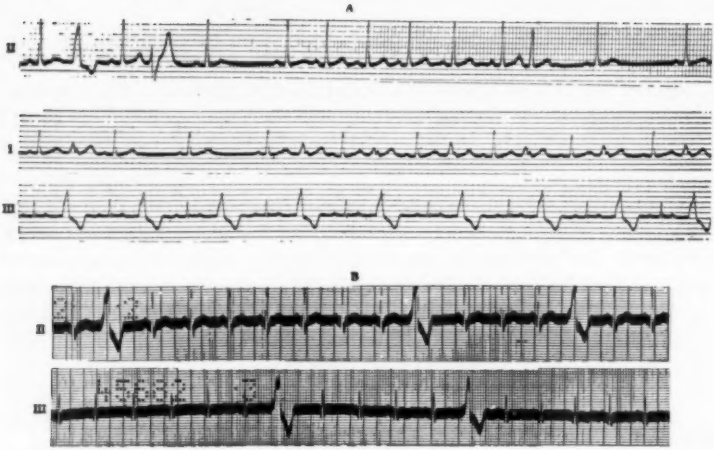

Fig. 85. Premature (ectopic) beats in childhood.

A, Auricular premature beats with varying ventricular response and intermittent bigeminy in a 15 year old boy with active rheumatic carditis. The upper strip (lead II) was recorded on a different occasion than the two lower strips (leads I and III). Time lines, 0.05 second. In lead II the sequence of sinus beats (rate 86 to 103) is temporarily disturbed by longer ventricular intervals, or by premature beats of 3 different contours. In either case the T waves of the last preceding sinus beats are distorted by superimposed premature P waves. The latter are of 2 types, a shallow notched and broad one, which is followed at a prolonged P-R by an upright bizzare ventricular complex (second beat of the strip), or by no QRS-T complex, resulting in the long ventricular pauses; the other premature P wave is tall and pointed and yields in one instance (fourth beat) a bizzare and widened QRS, and on another occasion (third last beat) a QRS-T of almost normal contour. The cause of this irregularity is auricular premature beats arising in 2 separate foci. They are either not conducted, or transmitted at a slow speed through the auriculoventricular junction (prolonged P-R), and partly also through the ventricles (aberrant ventricular conduction). In either case it is the normal refractory phase which interferes with normal conduction of the ectopic auricular impulses occurring too early in the cycle.

In the beginning of lead I two long ventricular intervals are seen; in the rest of the tracing there is an alternation of shorter and longer ventricular intervals (bigeminy). The beats terminating the longer cycles are of normal contour (and QRS duration) except for a particular notching in the S-T segment. They are sinus beats (as evidenced by the upright P wave preceding them at a normal P-R interval) coupled with auricular premature systoles. The beats terminating the shorter cycle are uniformly bizzare and have a widened QRS. They represent the aberrant ventricular response to the auricular premature systoles (conducted at a prolonged P-R interval). Since an identical notching of S-T is present in the sinus beats, initiating the 2 long intervals at the beginning of lead I, and, in addition, the latter are equal to those including a bizzare ventricular beat, the diagnosis of nonconducted auricular premature beats in this part of the record is established. Without close inspection of the S-T of the normal beats, the 2 long intervals could be mistaken for intermittent 2:1 sino-auricular block, and the premature bizarre beats for ectopic ventricular beats (cf. *B*) giving rise to intermittent ventricular bigeminy.

B, Ventricular premature beats in the presence of sinus tachycardia (in an 8 year old boy with internal hydrocephalus). The regular and fast (106) sequence of sinus beats is on 5 occasions disturbed by premature beats with widened QRS and bizzare contour. A notch in the upstroke of their QRS represents a sinus P wave, occurring at the expected time, but prevented from conduction to the ventricles by the earlier occurrence of the ectopic ventricular beat (interference in the auriculoventricular junction resulting in a fully compensatory pause). The uniform contour of the ectopic beats and the identical interval separating them from sinus beats (fixed coupling) suggest that a re-entry mechanism is responsible for their occurrence.

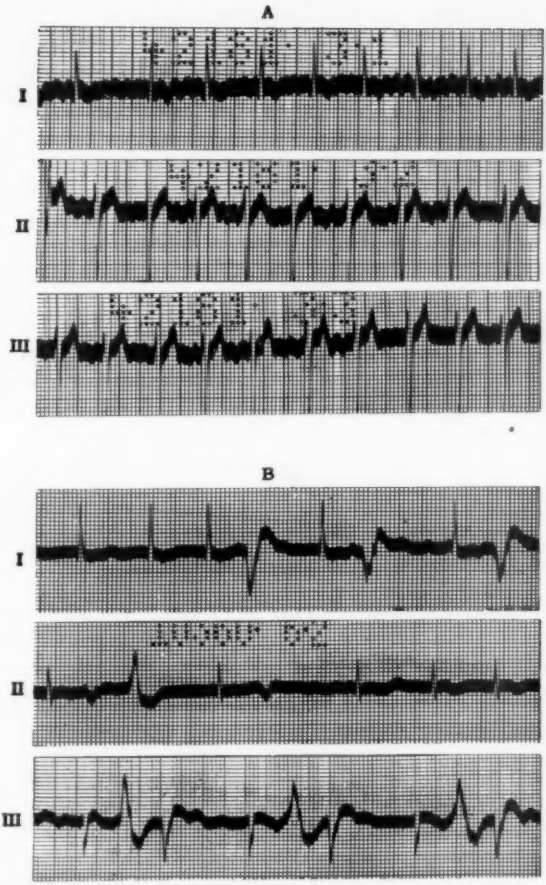

Fig. 86. Auricular fibrillation in childhood.

A, Record of a 4 year old mongoloid boy with cyanotic congenital heart disease (probably a common auriculoventricular ostium). The ventricular action is completely irregular with an average rate of 112; no P waves are seen, and the baseline is distorted by coarse, uneven and irregular undulations. This identifies the arrhythmia as auricular fibrillation. (The contour of the ventricular complexes is abnormal, owing to combined right and left ventricular strain, which was evident in the precordial leads, not shown.) The auricular fibrillation persisted in many subsequent records and was, therefore, considered to be chronic.

B, Record of a 10 year old girl with rheumatic heart disease. Auricular fibrillation is diagnosed as in *A*. The average ventricular rate is 110. Two types of ventricular complexes are seen. Those with a normal QRS duration (e.g., the first 3 beats in I, and the last 3 in II) represent conducted auricular impulses. The second type, with a bizzare and variable contour and a QRS prolonged over 0.12 second, represents ectopic ventricular premature beats. They occur singly or in pairs, at a fixed distance (coupled) to a conducted beat, and the 2 beats of a pair are opposite in direction of QRS and T. Ventricular premature beats with fixed coupling and variable contour are usually due to excessive digitalization, as was the case in this instance of chronic auricular fibrillation.

vanced mitral disease with congestive failure (Fig. 86, *B*). The establishment of auricular fibrillation is of grave prognostic significance in that the average duration of life after the onset of the abnormal rhythm is only ten months.[11] Paroxysmal auricular fibrillation may occur during the course of active rheumatic carditis[71] or may be precipitated by digitalis.[26] Its transient occurrence in a three month old infant has been reported.[20]

Auricular flutter, a mechanism closely related to auricular fibrillation, is less common in older children with advanced rheumatic heart disease, but is more common than auricular fibrillation in infants.[9, 32, 42] Unlike the adult, full (1:1) auriculoventricular conduction of auricular flutter is not uncommon in infants. Both auricular fibrillation and auricular flutter occur in cases of congenital heart disease associated with marked enlargement of one or both auricles like atrial septal defect, anomalous pulmonary venous drainage and Ebstein's disease[81] (Fig. 86, *A*). Actually, the number of cases with paroxysmal auricular flutter may be far greater than the reports in the literature indicate, since in many cases, classified as supraventricular paroxysmal tachycardia, the electrocardiogram does not permit ruling out auricular flutter with 1:1 ventricular response. Fortunately, from the standpoint of therapy, the distinction is unimportant since digitalis is the drug of choice in either condition and in auricular fibrillation as well. The difficulty of the electrocardiographic diagnosis is exemplified in Figure 87, *A*.

PAROXYSMAL TACHYCARDIA

The *classification* of paroxysmal tachycardia into supraventricular and ventricular forms is based primarily on the interpretation of the electrocardiogram obtained during an attack. On occasion the electrocardiographic differentiation may be extremely difficult, if not impossible, and the main criteria of ventricular paroxysmal tachycardia—irregular ventricular rate, presence of a slower and independent auricular rhythm, and widened QRS complexes—do not rule against a supraventricular origin of the ectopic pacemaker. The identification of ventricular captures, or of partial ventricular captures (ventricular fusion beats), is the most reliable clue for the differential diagnosis of supraventricular and ventricular tachycardia. The former can be diagnosed when the conducted and ectopic beats are identical in contour—regardless of QRS duration;[38] the latter is indicated by the presence of ventricular fusion beats[14] (cf. Fig. 88, *A*).

Ventricular paroxysmal tachycardia is rare in infants and children,[55, 67] and its etiology remains usually unknown. Of the infectious diseases of childhood, diphtheria is not infrequently the cause of ventricular paroxysmal tachycardia, usually a preterminal event.[10, 51, 76, 78] Recently an unusual case was reported of ventricular paroxysmal tachycardia in a six

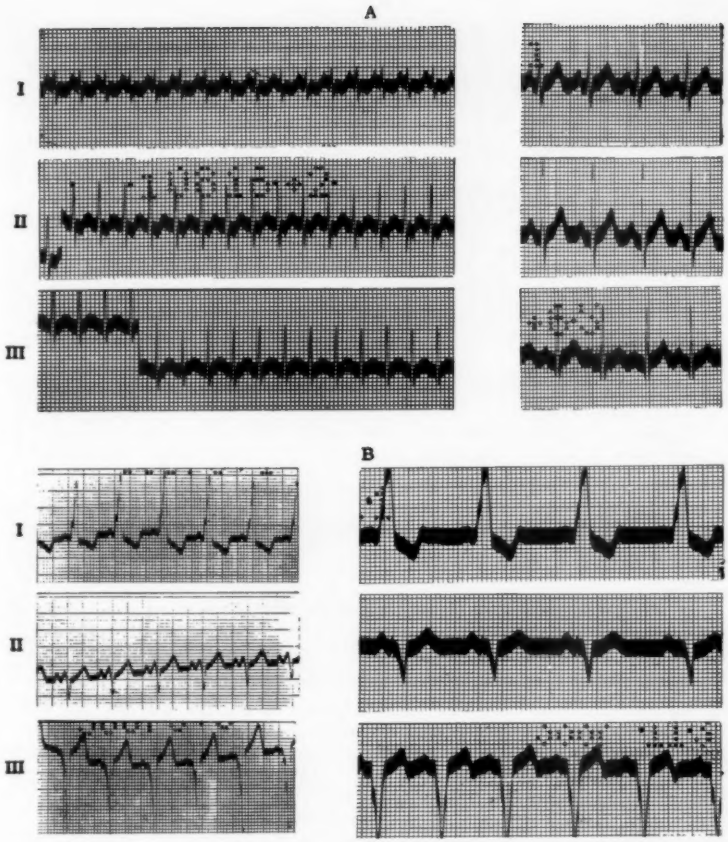

Fig. 87. A, Supraventricular paroxysmal tachycardia in a 3 month old infant. The record to the right was obtained several days after the record to the left. In the former is seen a rapid (250) and perfectly regular sequence of ventricular beats with normal (0.06 second) QRS duration—evidence of a supraventricular origin of the tachycardia. The type of auricular activity, which appears to be equally rapid, cannot be identified. Sinus tachycardia, however, can be ruled out in view of the excessive rate and by comparison with the tracing to the right, which shows the contour of the P waves during sinus rhythm (cf. Fig. 83, *A*). The rapid ventricular action could be due to (*a*) an ectopic auricular tachycardia with bizzare P waves preceding each QRS (cf. lead I) or (*b*) to an ectopic nodal tachycardia with retrograde P waves following each QRS (cf. lead II) or (*c*) to auricular flutter with a 1:1 ventricular response (which occurs more commonly in infants than in adults). In view of these difficulties of diagnosis this type of curve is termed most appropriately supraventricular paroxysmal tachycardia.

B, Record obtained in a case of Wolff-Parkinson-White syndrome with anomalous ventricular excitation persisting over 21 years. The 2 sets of curves are almost identical. Both show a short P-R interval (0.10 second)in combination with a bizzare QRS-T complex, widened mainly by a particular notching of the initial portion of QRS ("delta wave"). It is more pronounced (0.14 second) in the curve to the right than in that to the left (0.12 second). Both tracings were recorded in a healthy male, the first at the age of 4, the second at the age of 25. They are examples of the Wolff-Parkinson-White syndrome and represent one of the longest follow-up observations on record. [30, 49] This syndrome is frequently associated with attacks of supraventricular paroxysmal tachycardia of the type illustrated in *A*.

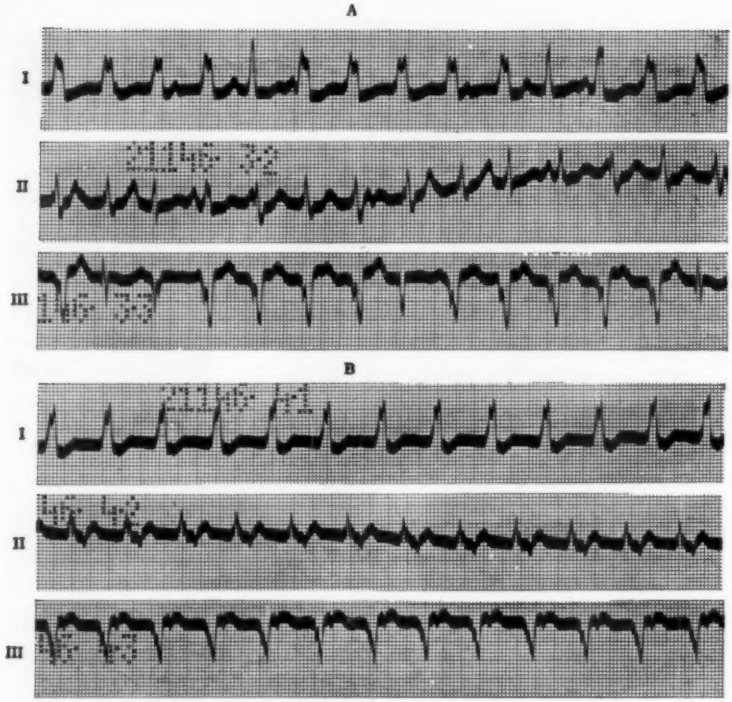

Fig. 88. Ventricular paroxysmal tachycardia in a 12 year old girl, with incomplete auriculoventricular dissociation (A) and persistent retrograde conduction. (B).

A, Three types of ventricular complexes are seen. The dominant beats are bizzare in contour, with QRS widened to 0.14 second. They occur at a faster rate (115) than that of the regular P waves (98), which are not fixed in the ventricular cycle. The 2 other types of ventricular beats have a varying and less bizzare contour and either a less prolonged or a normal QRS duration. They occur usually twice in succession, bear a definite relationship to a P wave, and the first one is "premature" (ventricular capture with a normal auriculoventricular conduction time). There is, therefore, auriculoventricular dissociation in the major part of the record due to enhanced activity of an idioventricular pacemaker discharging at a faster rate than the sinus node. Passage of most of the sinus impulses is prevented by interference in the auriculoventricular junction due to retrograde spread of the idioventricular impulses, but in no instance does the latter reach the auricles. Some of the sinus impulses, however, occur after the refractory period of the auriculoventricular junction is over, and succeed in traversing it. Some of them activate parts of the ventricles, while other parts remain under the control of the idioventricular impulse. This interference within the ventricles gives rise to the less bizzare *ventricular fusion beats*. The occurrence of the latter in a case of paroxysmal tachycardia represents evidence of the origin of the tachycardia in the ventricles. (Bizzare ventricular complexes per se are not necessarily evidence of a ventricular paroxysmal tachycardia. They may be seen in supraventricular tachycardia with a pre-existent intraventricular block or with development of aberrant ventricular conduction consequent to the rapid heart rate.)

B, Record taken on another occasion showing the same ventricular tachycardia as in *A*, at a slightly slower and uneven rate (averaging 100). All ventricular complexes resemble each other in contour and QRS duration and, in addition, are followed at a fixed interval of 0.18 second by a retrograde P wave. Thus here, similar to A, the idioventricular impulse spreads back towards the auricles, but, unlike A, succeeds in traversing the auriculoventricular junction and activating the auricles. Impulses of the sinus node are kept in abeyance either by interference of the sinus and idioventricular impulse close to the sinus node, or by constant retrograde discharge of the slower sinus pacemaker by the faster ectopic impulses.

year old girl after trauma to the chest.[82] Supraventricular paroxysmal tachycardia which refers to an ectopic pacemaker located above the bifurcation of the common bundle can be auricular or auriculoventricular nodal in origin.

It seems to us that the role of the auriculoventricular node as a center of active impulse formation was underestimated in the past and that many paroxysmal tachycardias were called auricular which can be interpreted as nodal in origin. The presence of a retrograde P wave pattern does not always permit distinction between auricular or nodal origin, and may also be noted in tachycardias of ventricular origin (Fig. 88, *B*). Furthermore, as pointed out before, the distinction between supraventricular tachycardia of auricular or nodal origin and auricular flutter may also be impossible. With ventricular rates of about 300 we should always consider the possibility of auricular flutter with 1:1 auriculoventricular conduction, and with regular ventricular rates of 150 to 180 we have to consider the possibility of auricular flutter with 2:1 auriculoventricular conduction or even sinus tachycardia (cf. Figs. 83, A, and 89, A). Carotid sinus pressure during the recording of lead V_1 or aV_R may occasionally clinch the diagnosis by revealing the auricular mechanism during a period of temporary depression of auriculoventricular conduction in the case of flutter, or by ending the attack of auricular or nodal tachycardia.

Treatment. Carotid sinus pressure is rarely successful in children. Bilateral carotid sinus pressure should be avoided.[55] The differentiation between ventricular and supraventricular tachycardia is more important clinically than that between the varieties of supraventricular tachycardia (including auricular flutter), since all of them tend to respond to digitalis medication. Most authors agree that digitalis is the drug of choice for the initial treatment of auricular flutter because of its depressant effect on auriculoventricular conduction; in contrast to such desirable slowing of the ventricles, quinidine and procaine amide (Pronestyl) may establish 1:1 auriculoventricular conduction in cases of auricular flutter with 2:1 auriculoventricular conduction.[53] A dose of 50 to 100 mg. of Digifolin by intramuscular injection, repeated in four to twelve hours, has been given successfully to infants with supraventricular paroxysmal tachycardia. Digitoxin, now also available in injectable form, in an approximate dose of 0.02 to 0.03 mg. per 0.5 kilogram in children under two years of age and 0.01 to 0.02 mg. per 0.5 kilogram over two years of age, has also been used.[55, 56]

If digitalis fails or if a more immediate effectiveness is imperative,[63] a parasympathomimetic drug should be tried. Of these the intravenous use of acetylcholine bromide has a definite advantage over Prostigmin and mecholyl. Its effect is fleeting and permits the repetition of a higher dose within a few minutes until the tachycardia is terminated.[73] The withdrawal of blood into the syringe containing acetylcholine has to be

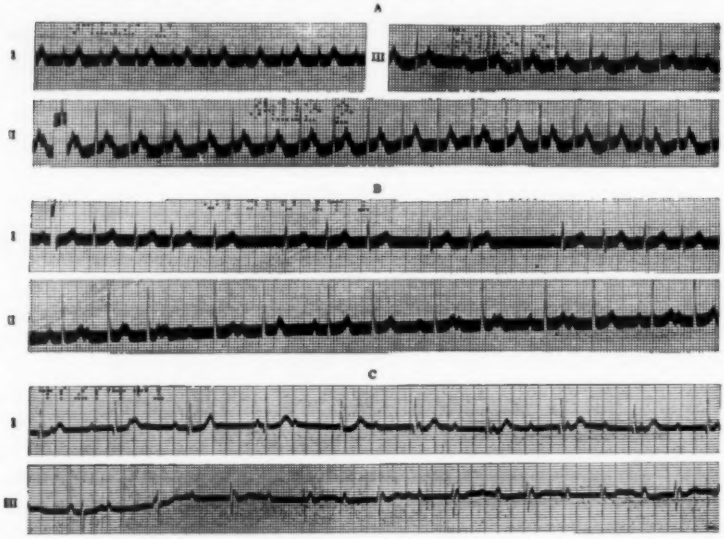

Fig. 89. Auriculoventricular block in childhood.

A, First degree auriculoventricular block during sinus tachycardia, imitating temporarily paroxysmal nodal tachycardia, in a 2 year old girl with rheumatic heart disease. In leads I and III no P waves appear to precede the ventricular complexes occurring in rapid (150) and regular succession. However, in a long strip of lead II a variable notching of the T wave is seen, proving the presence of upright P waves. They are superimposed on varying portions of the preceding T wave because (*a*) the cycle length is short and (*b*) the P-R interval is prolonged (to at least 0.26 second with slight variations). The presence of sinus tachycardia with first degree auriculoventricular block is thus established. On superficial inspection the record, especially the 2 short strips of leads I and III, could be mistaken for nodal tachycardia (with simultaneous activation of auricles and ventricles). The true mechanism in such cases is revealed in long strips showing variations of rate and/or P-R intervals, either spontaneously as here or after exercise or carotid sinus pressure.

B, Repetitive paroxysmal auricular tachycardia with second degree auriculoventricular block and the phenomenon of concealed auriculoventricular conduction in a 13 year old girl with rheumatic heart disease. Both the auricular and ventricular action are grossly irregular; longer and shorter periods of short and uneven cycles (average rate 136) are interrupted by single long cycles (corresponding to a rate of 58). Every QRS is related to a P wave (at variable P-R intervals), but not every P wave is followed by a QRS-T complex. P waves terminating long P-R intervals are identical in contour and associated with the shortest (0.20 second) P-R; P waves constituting the faster runs (partly superimposed on the ST-T of the preceding beat) differ in contour and show progressive increments of P-R duration from beat to beat, until one P wave is no longer followed by a ventricular complex, and the sequence starts again with a short P-R interval. There is, however, one exception: After the fourth P wave in lead II (superimposed on the S-T of the third ventricular complex) which is not followed by a QRS-T, the P-R interval remains prolonged—in fact, is the longest (0.34 second) of the entire tracing.

The interpretation of this complex arrhythmia is as follows: All ventricular complexes are conducted beats. The beats after long auricular pauses are sinus beats, and the beats constituting the faster rhythm are parts of an ectopic *repetitive auricular tachycardia*. The latter impulses are transmitted to the ventricles with progressive

avoided; otherwise the latter becomes inactivated. We recommend to start with 1 mg. and to increase every subsequent dose by 1 mg. In that way unpleasant reactions can be avoided; nevertheless, a syringe with atropine should be kept ready for intravenous use should cardiac arrest result. Prostigmin has been given successfully in a dosage of 0.5 to 1.0 mg. The use of mecholyl, which is frequently followed by severe reactions,[54] even fatal ones,[55] should be abandoned.

In some cases of supraventricular tachycardia digitalis proves also valuable in the prevention of attacks; however, quinidine (100 to 120 mg. daily in divided doses) is used more often for prophylactic therapy.

In the treatment of ventricular paroxysmal tachycardia, quinidine and procaine amide are the drugs of choice. To judge by the experience in adults,[6, 17] intramuscular rather than intravenous administration of procaine amide appears to be preferable when parenteral use is indicated to obtain an immediate effect or if oral medication is precluded. Although experience with procaine amide in children is still lacking, it may prove a safer drug than quinidine if a parenteral route is chosen to stop or slow a ventricular paroxysmal tachycardia. The tolerance for quinidine seems to be high in children,[52] and doses approaching those given to adults have been administered without ill effects.[34, 67, 72] Nevertheless, frequent electrocardiographic control is necessary in order to discontinue the medication if a widening of the QRS complexes becomes apparent. For the treatment of the acute attack Gold[28] recommends a dose of 3 mg. of

delay until one fails to traverse the auriculoventricular junction. This is the Wenckebach phenomenon, here due to an abnormal prolongation of the refractory period of the auriculoventricular junctional tissues (*second degree auriculoventricular block*). The occasional failure of the P-R interval to shorten after a dropped ventricular beat is ascribed to deep penetration into the auriculoventricular conduction system of this apparently nonconducted auricular impulse. Although this impulse fails to traverse the auriculoventricular junction and to activate the ventricles, a temporary refractory state is set up as if it were completely transmitted to the ventricles. Hence the transmission of the subsequent early impulse is delayed. This phenomenon has been referred to as *concealed auriculoventricular conduction*.[37]

C, Complete auriculoventricular dissociation due to advanced auriculoventricular block, probably complete auriculoventricular block, in a 6 year old boy with congenital heart disease (probably ventricular septal defect). There are more P waves than ventricular complexes. The latter occur in regular sequence at a rate of 54; the former (at an average rate of 93) are not fixed in the ventricular cycle and show a peculiar arryhthmia, P-R intervals including a QRS-T being shorter than P-R intervals without it. This particular type of sinus arrhythmia is commonly seen in advanced auriculoventricular block and is referred to as ventriculophasic sinus arrhythmia.[90] The persistently changing relationship of P and QRS-T indicates independent action of auricles and ventricles—*complete auriculoventricular dissociation*, the ventricles receiving impulses from a pacemaker located above the bifurcation of the common auriculoventricular bundle (normal QRS duration). The fact that the auricular rate is faster than that of the ventricles indicates that the auriculoventricular dissociation is due to *auriculoventricular block* (and not to simple physiologic interference). In all likelihood this block is complete; however, the possibility of an advanced form of second degree auriculoventricular block (e.g., 3:1 or 4:1) in which a slow ventricular action is prevented by persistent escape of a nodal pacemaker cannot be ruled out.

quinidine sulfate per pound of body weight given orally every three hours, or a similar dose of an injectable preparation intramuscularly. A 5 per cent suspension of quinidine sulfate in chocolate syrup may be prepared to mask the bitter taste of the tablets. Paroxysmal tachycardia (like premature beats) occurring during cardiac catheterization is usually transient, subsides spontaneously, and rarely requires specific treatment.

We had the opportunity to observe an unusual case of ventricular paroxysmal tachycardia in a child in which we resorted to surgical therapy (stellate ganglionectomy) after prolonged unsatisfactory medical treatment.[39]

A 12 year old girl gave a history of palpitation more or less persistent for over a year. Actual observation revealed an extrasystolic irregularity with marked variations in rate and paroxysmal acceleration of an ectopic ventricular pacemaker leading to syncopal attacks. The rate of the ectopic rhythm varied from 75 to over 200 and was usually over 105, whereas the rate of the sinus pacemaker varied from 54 to 150 and was usually over 90. Most electrocardiograms demonstrated a competition of the 2 pacemakers (Fig. 88, *A*), but occasionally both auricles and ventricles were under the control of the ectopic pacemaker (Fig. 88, *B*). Medical therapy, including bed rest, quinidine sulfate (6 grains every 3 hours), potassium chloride, magnesium sulfate and digitalis, was unsuccessful. Mecholyl given by subcutaneous injection of 12.5 to 25 mg. abolished the ectopic pacemaker within 5 minutes; however, within 25 minutes the abnormal beats started to reappear. Mecholyl and prostigmin given by mouth had a less reliable effect.

Resection of the right stellate and second thoracic ganglia was followed after 48 hours by marked depression and within a week by complete elimination of the ectopic pacemaker responsible for the rapid heart action. Within 6 weeks after the operation the heart had decreased considerably in size and appeared normal in every respect 5 months after the operation.

One month later, however, the patient experienced the first recurrence of a spell of very rapid heart action—the electrocardiogram showed the same ectopic pacemaker—and in the subsequent weeks such spells became more frequent, signs of left heart strain appeared in the electrocardiogram, and the heart became enlarged. Three months after the first recurrence of her tachycardia it was decided to subject the patient to the same surgical procedure on the left side. Unfortunately the patient died on the operating table; the cause of death remained obscure, since cardioscopic observation at the time of death revealed cardiac standstill preceded by a normal sinus rhythm at a rate of 80 and no paroxysm of tachycardia. Postmortem examination showed fatty infiltration of the right ventricle and right auricle and marked fatty infiltration and degeneration in the region of the sino-auricular node. There was no evidence of a valvular lesion, no congenital defect, and the coronary arteries were normal.

Paroxysmal Tachycardia in Young Infants

In 1941 Hubbard[33] pointed out the common occurrence of paroxysmal tachycardia in infants and described its distinctive clinical course, which differs from that of paroxysmal tachycardia in children or adults. Since then the clinical entity of paroxysmal tachycardia in infants has been firmly established.[27, 55] Mostly infants in the first four months of life are affected (Fig. 87, *A*). The heart rate tends to be rapid (250 to 300), and was as high as 360 in a desperately ill infant treated successfully with intravenous acetylcholine bromide.[63] If the tachycardia is not recognized

and is permitted to continue for several days, congestive failure invariably ensues.

The early symptoms associated with the attack are restlessness, vomiting, pallor and cyanosis. Leukocytosis and rise in temperature may be present without evidence of an associated infection. A chest roentgenogram may soon reveal cardiomegaly and pulmonary congestion; the liver enlarges quickly, and congestive failure progresses rapidly unless the tachycardia is terminated. The electrocardiogram almost invariably reveals a tachycardia of supraventricular origin. In the majority of cases no concomitant heart disease can be found.

Recurrences of paroxysmal tachycardia do not tend to extend beyond the first year—with the exception of those associated with the Wolff-Parkinson-White syndrome—and not infrequently no further attacks beyond the initial one occur. Treatment should be initiated immediately before the signs of congestive failure become manifest, which is only possible with an early diagnosis based upon an attempt to determine the cardiac rate, a simple procedure which may establish the diagnosis before confirmation by the electrocardiogram. Thus, if recognized early and adequately treated, this serious condition has an excellent prognosis.

Repetitive Paroxysmal Tachycardia

Judging by the paucity of reports in the pediatric literature, "repetitive paroxysmal tachycardia,"[61] which differs in several aspects from the common form of continuous paroxysmal tachycardia, has not yet become fully established as a clinical entity. This type of paroxysmal tachycardia cannot be recognized clinically; its diagnosis rests upon the electrocardiographic findings. It is characterized by "recurrent short runs of auricular, nodal or ventricular extrasystoles, runs of paroxysmal tachycardia in fact, almost constantly present for months or for years and only occasionally interrupted by the normal sinus rhythm."[61] In fact, typical instances of this form of irregular heart action were recognized as a special form of paroxysmal tachycardia earlier by Gallavardin (*extra-systolie a paroxysmes tachycardiques*[22] or *tachycardie en salves*[32] and by Froment[20] (*extra-systolie ventriculaire bénigne a paroxysmes tachycardiques*).

Of the 40 cases of this variety of tachycardia observed by Parkinson and Papp over a great number of years, 7 occurred in children. It is significant that only 3 patients of the entire series had evidence of organic heart disease. In the majority of the cases the tachycardia is supraventricular in origin and is tolerated well because its rate is not excessive, on the average 150 in children. When, however, the tachycardia is of ventricular origin, the patients are more prone to rapid rates which may give rise to syncopal attacks.[24, 61] The usual symptom is palpitation, frequently initiated by exertion, emotion or posture.

In general, the disability caused by the irregular heart beat is surprisingly slight. Parkinson and Papp[61] and Scherf and Schott[70] call the results of treatment with digitalis or quinidine disappointing, but in the ventricular form quinidine has been used successfully in many instances. The prognosis is good in the majority of cases, though the attacks may last from childhood until adolescence with a definite tendency for the state of repetitive tachycardia to subside. As pointed out by Parkinson and Papp, this form of paroxysmal tachycardia is one of the few conditions in children which they are likely to "grow out of." An instance of repetitive auricular tachycardia (associated with second degree auriculoventricular block) is illustrated in Figure 89, *B*.

THE WOLFF-PARKINSON-WHITE SYNDROME (W-P-W SYNDROME)

Although Wolff, Parkinson and White in their original report,[91] which included the case of a sixteen year old patient, pointed out that a congenital anomaly may be responsible for the syndrome, it was not until eleven years later that the first case of an infant showing the syndrome was reported.[57] In 1945 Lind[46] counted 29 cases of Wolff-Parkinson-White syndrome in children reported in the literature, and since then a number of other cases, particularly in infants, have been added. Four of the cases in Lind's series had evidence of congenital heart disease. The practical significance of the Wolff-Parkinson-White syndrome lies in the frequent association of the electrocardiographic anomaly with paroxysmal tachycardia. The latter is practically always of a supraventricular type. In adults the syndrome is occasionally associated with paroxysmal auricular fibrillation, and the presence of the anomalous ventricular complexes during the attack may imitate ventricular paroxysmal tachycardia.[40] To our knowledge only one instance suggesting such a mechanism has been reported in a child.[44]

Mannheimer[50] pointed out that the criteria for the electrocardiographic diagnosis of the Wolff-Parkinson-White syndrome in infants are somewhat different from those in adults, since at this age the normal P-R interval measures less than 0.12 second and the normal QRS complex does not exceed 0.09 second in duration. The main diagnostic feature is the contour of the QRS complex with the characteristic initial notching, the "delta wave."

Although in general the prognosis of the Wolff-Parkinson-White syndrome is considered to be excellent if there is no evidence of organic heart disease (cf. Fig. 87, *B*), a number of fatalities resulting from paroxysmal tachycardia have been reported,[2, 36] among them two deaths occurring in infants.[36, 75] It was pointed out before that in infants prolonged attacks of paroxysmal tachycardia with rapid rates, if unrecognized and untreated, may rapidly lead to congestive failure and death.

As a rule, the diagnosis of the Wolff-Parkinson-White syndrome cannot be made from the electrocardiogram obtained during the attack of paroxysmal tachycardia and may only be revealed by a record taken between attacks. Hence the importance of a follow-up examination after cessation of an attack of paroxysmal tachycardia. Conversely, the finding of the Wolff-Parkinson-White syndrome between attacks suggests the diagnosis of paroxysmal tachycardia. In children with the Wolff-Parkinson-White syndrome recurrences of attacks appear to be more frequent than in patients with supraventricular tachycardia without the Wolff-Parkinson-White syndrome.[55]

HEART BLOCK

The manifestation of a disturbance in conduction of the cardiac impulse depends on two main factors: the localization and extent of the lesion involving the conduction system, and the readiness of potential subsidiary pacemakers to take over the command according to their inherent automaticity if the impulse of a higher pacemaker fails to activate the heart.

Simple prolongation of the auriculoventricular conduction time beyond 0.12 second in infants and beyond 0.16 to 0.18 second in children, and delayed or completely blocked conduction in one bundle branch or its arborization ("bundle branch system block"[35]) do not lead to a change in rate or rhythm and are primarily electrocardiographic diagnoses. Occasionally the former can be suspected if a gallop rhythm develops without change in rate, or the first heart sound becomes less distinct, or a presystolic murmur changes to a mid-diastolic one. The latter, bundle branch system block, is uncommon in children except in diphtheria,[79] and the frequent occurrence of right-sided intraventricular conduction defects in congenital heart disease with chronic right heart strain, particularly in atrial septal defect.[4]

Sino-auricular block is usually an acquired and temporary disturbance due to infection,[57] particularly scarlet fever, diphtheria or rheumatic fever, and does not require any therapy.

Auriculoventricular block may be either acquired or congenital. *Acquired auriculoventricular block* manifests itself usually as first degree block (simple prolongation of the auriculoventricular conduction time—cf. Fig. 89, *A*) or as third degree (complete) auriculoventricular block leading to complete auriculoventricular dissociation. Second degree auriculoventricular block with occasional or regularly dropped ventricular beats is less common in children; an example is seen in Figure 89, *B*.

A diagnosis of complete auriculoventricular block with a ventricular rate over 50 does not necessarily indicate the complete failure of the auriculoventricular junction to transmit auricular impulses. The relatively

high rhythmicity of the subsidiary pacemaker in childhood, and its continuous escape, may prevent the manifestation of a high degree partial auriculoventricular block. Any form of auriculoventricular block may be precipitated by the exhibition of digitalis. However, unless excessive doses of the drug are administered, such digitalis block occurs primarily in the presence of a latent active infection. The latter is particularly suggested when considerable variations in auriculoventricular block occur over a short period of time. Thus rheumatic fever and scarlet fever[64, 88] may be responsible for second degree auriculoventricular block with "dropped beats" preceded by progressive lengthening of the conduction time (the Wenckebach phenomenon), or for more advanced second degree auriculoventricular block like 2:1 block. Complete auriculoventricular block due to rheumatic fever tends to be reversible, but occurring in diphtheria[31, 76] is usually a terminal event. Mumps was reported to produce temporary complete auriculoventricular block.[68] A case of fibroelastosis with complete auriculoventricular block has been observed.[77] Complete auriculoventricular block associated with congenital heart disease may still be an acquired affection.[66, 83, 93] An unusual case is on record of complete auriculoventricular block developing gradually in the neonatal period.[74]

Congenital Auriculoventricular Block

Congenital auriculoventricular block is usually complete with a ventricular pacemaker located above the bifurcation of the common bundle. The ventricular rate is about 80 in infants and 54 to 66 in young children with an acceleration of 10 to 20 beats per minute on exercise. Auriculoventricular block is as frequently associated with atrial septal defects as with defects of the ventricular septum.[81] Most cases of patency of the ventricular septum, including those with almost complete absence of the ventricular septum, are not associated with defects of the conduction system.[95] Thorough histologic examination of hearts with complete congenital heart block[92, 94, 95] revealed a developmental defect of the bundle of His rather than a mechanical interruption of a normally developed conduction system by a septal defect. Prognosis depends primarily on the associated malformation. Many patients are asymptomatic, require no therapy, and live a long and active life.[7, 8] Yet Adams-Stokes attacks occur in about 20 per cent of the cases of congenital complete auriculoventricular block and may be the cause of sudden death.

In a number of cases the presence of auriculoventricular block was diagnosed before birth on account of the slow fetal heart rate.[25] A few instances of congenital complete auriculoventricular block occurring in two siblings are on record,[1, 3, 87] suggesting the existence of a rare familial form of congenital complete auriculoventricular block. An instance of

congenital, probably complete, auriculoventricular block is illustrated in Figure 89, *C*.

Adams-Stokes Attack

Adams-Stokes disease is a name applicable to patients with heart block who suffer from recurrent attacks of loss of consciousness due to ventricular standstill, ventricular tachycardia, ventricular fibrillation, or a combination of these.[62] Ventricular standstill may develop at the transition from 1:1 auriculoventricular conduction[83] or from second degree auriculoventricular block to complete auriculoventricular block, or, more often, during complete auriculoventricular block[19] as a result of slowing or stoppage of the ventricular pacemaker. Actually, in children the mechanism of the Adams-Stokes attack has not been studied as carefully as that of the attack in the adult,[62] in whom only about half of the attacks proved to be due to ventricular standstill, whereas the other half were due to ventricular tachycardia followed by ventricular standstill, or ventricular tachycardia without ventricular standstill. A few rare cases are on record in which Adams-Stokes attacks due to complete auriculoventricular block were entirely neurogenic (vagal) in origin.[45, 84] As pointed out before, syncopal attacks similar to the attacks of Adams-Stokes disease occur in patients with paroxysmal tachycardia in the absence of auriculoventricular block.[5, 21, 24, 89]

A differentiation is of considerable importance in view of the different management of such spells from those associated with auriculoventricular block. For the treatment or prevention of cardiac standstill sympathomimetic drugs should be used. Recently a promising new compound, isopropyl norepinephrine (Isuprel), has been introduced.[58] Isuprel increases the rhythmicity of the higher pacemakers, has little or no pressure action, and does not predispose to ventricular fibrillation. It is about five times as potent as epinephrine and can be administered parenterally or sublingually. More recently a simple apparatus for electrical stimulation of the heart has become available[96] and may prove lifesaving in certain cases of Adams-Stokes disease.

SUMMARY

1. The common disturbances in infants and children of formation and conduction of the cardiac impulse are discussed from both the standpoint of electrocardiographic diagnosis and clinical significance and are illustrated by representative electrocardiograms.

2. A historical review and a clinical appraisal are presented of the three outstanding recent developments in the field of the cardiac arrhythmias in infants and children, viz., (*a*) recognition of paroxysmal tachycardia

in early infancy as a clinical entity, (*b*) recognition of "repetitive paroyxsmal tachycardia" as a clinical entity, and (*c*) recognition of the occurrence and significance of the Wolff-Parkinson-White syndrome in infants and children.

3. The common occurrence of auriculoventricular dissociation without auriculoventricular block in active rheumatic carditis, and its significance as evidence thereof, is emphasized. An unusual case of ventricular paroxysmal tachycardia treated with stellate ganglionectomy is presented.

4. The therapy of the various cardiac arrhythmias is outlined, including the use of recently introduced drugs and methods.

The authors are indebted to Dr. L. N. Katz for valuable criticism.

Limitations of space make it necessary to omit the references here. They will appear, however, in the authors' reprints.

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CARDIAC HYPERTROPHY IN INFANCY

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Few problems in the modern history of congenital heart disease have stimulated as much academic interest and study as the problem of cardiac hypertrophy in infancy. At the inception of the modern era of congenital cardiac disease a large number of abnormal hearts with cardiac enlargement were grouped under the term "idiopathic hypertrophy." Included in this group were all those hearts which had greater than normal size and weight without a distinct congenital anomaly or known cardiac disease which could account for the enlargement.

As time progressed and the number of cases reported in the literature increased, interest also mounted, culminating in an etiologic classification and, in most instances, accurate clinical descriptions. Many cases were found to be due to extrinsic causes, such as pulmonary fibrosis, congenital renal anomalies, hemolytic anemias and biliary atresia. As the etiology was discovered, these hearts were dropped from the group of "idiopathic hypertrophy," and emphasis was rightly placed on the primary pathology and not on the secondary cardiac hypertrophy.

The first definitive step toward an etiologic diagnosis in the remaining hearts with "idiopathic hypertrophy" came in 1924, when Carrington and Krumbhaar[8] described an anomalous left coronary artery originating from the pulmonary artery, and suggested that perhaps many of the myocardial hypertrophies in infancy were due to this cause. In 1932 Pompe[33, 34] and Bishoff[6] and Putscher[38] independently described glycogen storage disease of the heart. Gradually most of the hearts previously described as "idiopathic hypertrophy" have become segregated into well recognized pathologic entities.

The next step following pathologic classification was clinical recognition. In most instances enough cases have been reported so that correct clinical diagnoses are being made with increasing frequency. The last step and future hope is that with newer surgical techniques and increased

metabolic studies, discoveries for the correction and cure of most of these diseases may be possible.

ABERRANT LEFT CORONARY ARTERY ORIGINATING FROM THE PULMONARY ARTERY

Origin of the left coronary artery from the pulmonary artery is, in all likelihood, a commoner malformation than the literature would indicate. Thirty-eight instances of this anomaly have been reported; however, of about 300 hearts in the Children's Memorial Hospital collection, there are five specimens with this defect—an incidence of about 1.7 per cent of all congenital cardiac malformations autopsied.

The aberrant coronary artery is probably due to a faulty origin of its anlage in the aortic bulb. Thus when the bulbar septum divides the common trunk into the two great vessels, the left coronary artery remains with the pulmonary artery. A few still believe that the coronary artery may be the result of the bulbar septum forming in the wrong plane, thus placing one of the aortic valve cusps in the pulmonary artery and one of the pulmonary valve cusps in the aorta. The absence of an associated defect makes this latter improbable, for if the bulbar septum is in one plane and the fusing endocardial cushions in another, one should expect an interventricular septal defect in at least a few specimens.

Origin of the left coronary artery from the pulmonary artery has no noticeable effect upon cardiac physiology during intrauterine life. At birth, however, two primary alterations in cardiac physiology take place. The venous blood perfusing the left ventricle through the coronary artery becomes low in oxygen content and is supplied at a greatly reduced arterial pressure. It is the signs, symptoms and laboratory findings of severe left ventricular anoxia which make the diagnosis of this anomaly possible.

Pathology. Pathologically, these hearts reflect almost perfectly the physiologic alterations which are present. The gross specimen weighs two to four times the normal weight. The left ventricle is firm and fibrous with marked dilatation and hypertrophy of the surviving muscle fibers. The endocardium is grayish-white, and cut surface of the myocardium reveals large areas replaced by gray fibrous tissue. The apical region of the left ventricle is often thin and aneurysmally dilated. All stages of myocardial degeneration may be seen microscopically with calcification, fibrosis and, in a few areas, early degeneration with round cell infiltration. Scarring is usually most prominent in the midzone and inner zone of cardiac muscle and least prominent in the epimyocardium. Subendocardial fibroelastosis of the diffuse type is always present in the left ventricle. Left coronary artery thromboses are frequent in the smaller arteriole branches, probably owing to the low arterial pressure and usually accompanied by severe dilatation of the subendocardial sinusoids.

Symptoms, Signs and Laboratory Findings. The onset of symptoms in all the cases from this hospital was within the first month of life. This is also true of approximately half of the reported cases in the literature. The other half had a more acute onset, usually within three weeks prior to death. In some instances the history will date back to a respiratory infection or pneumonia, since these patients are apparently more susceptible than normal infants. Despite the variance in onset, the symptomatology is usually the same. The parent complains that the infant breathes rapidly, takes a long time to feed, and that there is a progressive diminution in weight gain. Not infrequently a history of vomiting is elicited. About one to three weeks before death, episodes resembling angina in the adult begin. These are usually associated with feeding or exertion. The patient will appear normally active and alert; then suddenly the expression will change to one of apprehension. The infant will become motionless, with its legs pulled onto its chest, and barely breathing. A faint tinge of cyanosis may appear, rapidly followed by extreme pallor and rapid shallow respirations. Profuse perspiration covers the body, and the baby begins to scream as though in severe pain. These episodes usually last three to ten minutes and leave the baby limp and exhausted. They become progressively more frequent until the infant dies. The average age at death is four and a half months. The youngest infant reported in the literature died at two months of age and the oldest at thirteen months of age. A few patients have lived to adulthood; however, in these cases there were free anastomoses between the right and left coronary arteries, and the left coronary artery had the structural characteristics of a vein.

Physical examination usually reveals a slightly undernourished infant with rapid shallow respirations and moderate tachycardia. The heart is grossly enlarged, the apex palpable about 2 cm. outside the nipple line in the fifth interspace. A murmur is usually absent, but, when present, is a soft, apical systolic murmur. There are usually no signs of cardiac failure. Roentgenography and fluoroscopy of the chest show a grossly enlarged heart, the enlargement being mainly of the left ventricle. An aneurysm of the apex of the left ventricle is sometimes noted and is almost diagnostic of an aberrant left coronary artery from the pulmonary artery. There is usually atelectasis of the left lower lobe, either complete or partial, due to the left ventricular enlargement. The electrocardiogram usually resembles that of an anterior myocardial infarction in the adult. This also may be diagnostic if present. The commonest electrocardiographic findings are as follows: (1) tachycardia; (2) in lead I—deep Q wave, S-T segment elevation with coving, and inverted T wave; (3) in lead III—upright QRS complex, S-T segment depression, and upright T wave (reciprocal changes); (4) in lead CF_5—deep Q wave with inversion of QRS complex and small R wave, S-T segment elevation, and inverted T wave.

Correction. With increasing frequency the anomalous left coronary

Fig. 90. *A*, Endocardial fibroelastosis. Left ventricle. Note extremely thick and smooth endocardium with marked dilatation and hypertrophy. *B*, Aberrant left coronary artery originating from the pulmonary artery. Left ventricle. There is marked dilatation and moderate hypertrophy. Note thinness of the apical left ventricle. Endocardium again is slightly thickened. Single coronary visible in aorta. *C*, Rhabdomyoma. Note the multple nodules protruding from the endocardial surface of the heart. *D*, Endocardial fibroelastosis from a heart with multiple congenital anomalies. Note the elastic tissue extending with the fibrous tissue deep into the myocardium. (Verhoff's elastic tissue stain. H.P. × 200.) *E*, Endocardial fibroelastosis without other congenital anomalies. There is marked fibrosis and elastic tissue hyperplasia of the endocardium, and there is also some subendothelial sinusoidal dilatation. (Verhoff's elastic tissue stain. H.P. × 100.) *F*, Aberrant left coronary artery originating from the pulmonary artery. (Hemotoxylin-eosin stain. H. P. × 200.) A small coronary artery showing thrombosis with slight recanalization. *G*, Rhabdomyoma, showing spider cells and cross striations. Note the vacuoles. (Phosphotungstic acid-hemotoxylin stain. H.P. × 250.) *H*, Glycogen storage disease. Note the vacuolation and swelling of the cells with the peripheral sarcoplasm. (H & E stain. H.P. × 100.)

artery originating from the pulmonary artery is being diagnosed before death rather than at the autopsy table. Already unsuccessful attempts at surgical intervention have been tried. There is little doubt that in the foreseeable future a successful surgical procedure will be found for correcting this anomaly. Doubt remains, however, that any surgical correction will offer added life to the patient unless a diagnosis can be made early in life, before the severe irreversible changes seen at the autopsy table have taken place.

GLYCOGEN STORAGE DISEASE OF THE HEART

Excessive glycogen storage in the heart is a rare disease whose primary clinical importance lies in its differential diagnosis from the other causes of cardiac hypertrophy in infancy. There are only 15 authenticated cases reported in the literature, and there is only one specimen in the 300 congenitally malformed hearts of the Children's Memorial Hospital collection—an incidence of 0.33 per cent.

This disease is in all probability of metabolic origin, although the etiology and pathogenesis are unknown. At present the excessive glycogen deposition is thought to be due either to an abnormal glycogen molecule which is difficult for the cell to metabolize, or to the inability of the body to change glucose to fat, and therefore all excess glucose must be utilized or stored as glycogen. Neither of these theories explains why the heart is the primary organ involved.

Although glycogen storage disease of the heart primarily affects the heart both clinically and pathologically, a careful postmortem study will reveal excessive glycogen deposits in nearly all tissues of the body, particularly skeletal muscle and liver. The excessive glycogen in the liver, however, is hardly comparable to that seen in von Gierke's disease; although both diseases are due to disturbance in glycogen metabolism, they are in reality two separate entities which are dissimilar in their physiology, pathology, and clinical and laboratory findings.

Pathology. Grossly, the heart is about four times normal size and in situ fills the entire anterior chest. The enlargement is predominantly ventricular and primarily left ventricle. The cut surface is pale, light pink and hard. Microscopic sections stained with hematoxylin-eosin stain reveal large swollen muscle cells with a centrally located nucleus surrounded by a large vacuolated area. Within this area one may see a fine reticulum resembling a spider web. The periphery of the muscle cell consists of sarcoplasm with easily visible cross striations. There is no cellular infiltration or fibrosis. The endocardium may have a slight fibroelastic tissue thickening.

Symptoms, Signs and Laboratory Findings. Onset of symptoms usually occurs shortly after birth; in about one third of the reported cases, how-

ever, the onset varied between one and six months after birth. The infants with glycogen storage disease of the heart averaged five months of life—the youngest died at five weeks and the oldest at eight months. A positive family history was present in 3 of 16 cases.

Symptoms frequently begin with poor feeding, failure to gain weight properly, and rapid breathing. The infant (early in life) is usually listless and rarely cries. There is often a history of cyanosis following feeding. The poor feeding, listlessness and dyspnea are progressive, and in the last few weeks the patient begins to lose weight and becomes irritable. The dyspnea is severe, and the patient rarely sleeps, crying most of the time.

Early in life the physical examination will reveal a slightly malnourished, listless infant with poor muscle tone and depressed deep reflexes. The heart is enlarged, but no murmur is present. Tachycardia and rapid respirations may be noted. A macroglossia is present in about one third of the cases, and an enlarged liver is frequently found.

As the disease progresses, the dyspnea and tachycardia increase. Muscle tone remains poor, and the heart continues to enlarge. Late in the disease a systolic murmur may be heard over the entire precordium and back, but is best localized in the fourth left interspace. These patients nearly always die in cardiac failure, often complicated by an upper respiratory infection or pneumonia.

Abnormal laboratory findings are limited to the radiologic survey and the electrocardiograms. Roentgenograms and fluoroscopy of the chest reveal an enlarged globular heart with both right and left ventricular hypertrophy. The trachea and esophagus are compressed and displaced dorsally. Atelectasis of the left lower lobe of the lung is frequently encountered, owing to the extreme cardiac enlargement.

Five electrocardiograms are reported in the literature, and four of these were reviewed for this article. In almost every detail these four electrocardiograms were the same and consisted of the following: (1) QRS complex tall and upright in leads I and II and inverted in lead III; (2) S-T segment depressed in all standard leads; (3) T wave inverted in all standard leads; (4) S-T segment elevated in leads CF_2 and CF_4 and inverted in CF_5; (5) T wave upright in lead CF_2, biphasic in lead CF_4 and inverted in CF_5. This remarkable similarity of electrocardiographic findings is of interest, but the number of cases is too small for any definite conclusions.

Muscle biopsy is the only diagnostic test for glycogen storage disease of the heart. The skeletal muscle, when stained properly either by Best's carmine or periodic acid, will reveal a marked excess of glycogen-like material within the cells. A positive muscle biopsy in association with extreme cardiac enlargement is almost conclusive evidence of glycogen storage disease of the heart.

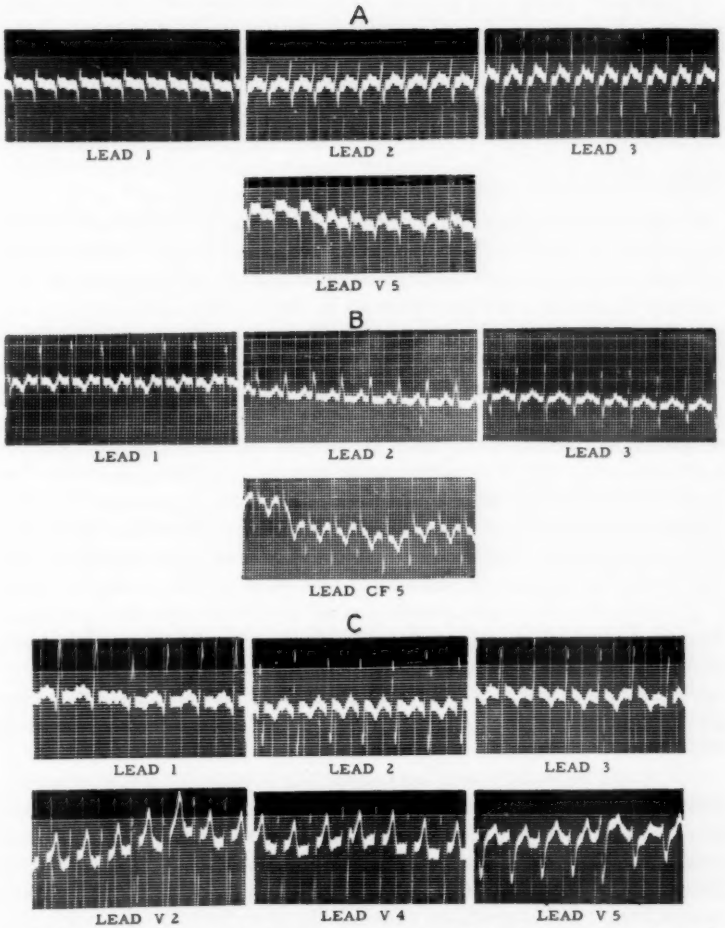

Fig. 91. *A*, Typical case of aberrant left coronary artery originating from the pulmonary artery. Lead I: deep Q wave, elevated S-T segment (and slight coving), inverted T wave. Lead III: reciprocal changes with depressed S-T segment, upright T wave. Lead CF_5: deep Q wave, elevated S-T segment, inverted T wave. *B*, Atypical aberrant left coronary. Lead 1: small Q wave, S-T segment not elevated, but tending to coving, inverted T wave. Lead 3: S-T segment not depressed, upright T wave. Lead CF_5: deep Q wave, upright QRS, inverted T wave. *C*, Endocardial fibroelastosis. Nonspecific left heart strain pattern. Note T wave inverted in all standard leads and S-T segment elevated. Note also small Q wave in lead I and slight coving of S-T segment.

Treatment. There is at present no successful method of treating this disease, which invariably ends fatally in early infancy. The approach to treatment must be made through metabolic studies. Perhaps after the etiology and pathogenesis have been determined a means of therapy may be discovered.

RHABDOMYOMA

Congenital rhabdomyoma is one of the less frequent causes of cardiac hypertrophy in infancy. It is thought by most authors to be a congenital anomaly and may involve the heart either as a single nodule or as multiple nodules. Sixty-five cases are reported in the literature, and 2 cases are present in the heart collection at the Children's Memorial Hospital—an incidence of 0.66 per cent.

In about 90 per cent of the reported cases multiple nodules were scattered throughout the ventricular and atrial musculature. The heart usually weighs about one and a half times to twice the normal weight and is unremarkable except for the small to moderately large grayish-yellow tumors, easily visible throughout the myocardium. On microscopic section the nodules are composed of large vacuolated cells surrounded by a thin layer of sarcoplasm. The nuclei are also large and contain a prominent nucleosus. From the nucleus, strands radiate outward, giving rise to the term "spider cell." Cross striations are best seen by the use of special stains, such as phosphotungstic acid-hematoxylin. These cells are said to closely resemble immature cardiac muscle cells. The edge of the tumor mass usually ends abruptly; however, a gradual transition may take place. The vacuoles are thought to contain glycogen, but Hertzog[23] has recently questioned this.

Clinically, there are usually no cardiac *symptoms* until the patient suddenly dies. Occasionally, a nodule may be located on a valve, giving rise to a murmur, or it may interfere with conduction, causing an arrhythmia or a heart block. The diagnosis, however, is made at the autopsy table. Cyanosis and dyspnea are the commonest symptoms and occur within several hours prior to death. In over half the cases death occurs within the first year of life, and in over one fourth of the cases shortly after birth.

Congenital rhabdomyoma of the heart is frequently associated with other congenital defects. Over 50 per cent of the reported cases are associated with tuberous sclerosis. Cleft palate, harelip, adenoma sebaceum, renal cysts and tumors, and many other congenital anomalies, are less frequently associated with this disease.

At the present time there is little hope for patients with this disease. Premortem diagnosis is almost impossible, and there is no satisfactory treatment.

ENDOCARDIAL FIBROELASTOSIS

The hearts with endocardial fibroelastosis are the commonest but also the most complex group of congenital anomalies which cause cardiac hypertrophy in infancy. This complexity arises mainly from the variability of anatomic structure of the heart, as well as the numerous associated vascular anomalies. Thus one may find endocardial fibroelastosis in the left atrium and ventricle of a specimen in which these structures are small and thick walled, or they may be dilated chambers with thick musculature. The presence of diffuse endocardial fibroelastosis almost invariably causes cardiac hypertrophy in the adjacent ventricular musculature, probably due to the increased work necessary to contract and expand the thick fibroelastic tissue of the endocardium. The most common abnormalities associated with endocardial fibroelastosis are bicuspid aortic valve, hypoplasia of the aorta, fetal type of coarctation of the aorta, patent ductus arteriosus, and mitral or aortic valvular stenosis or atresia. In specimens with a small left atrium and ventricle one frequently finds a patent foramen ovale.

The *etiology* of endocardial fibroelastosis has been attributed by various authors to many causes. The early writers believed that this finding was due to intrauterine infection or perhaps a generalized metabolic disease. Later authors explained the endocardial thickening as a congenital anomaly. More recently endocardial fibroelastosis has been described as a secondary phenomenon occurring in association with certain types of congenital anomalies which tend to produce intrauterine ventricular chamber anoxia and disturbance in the coronary arterial and ventricular chamber pressure relationships.

The incidence of endocardial fibroelastosis in the literature is difficult to determine, since often these hearts are reported due mainly to their associated anomaly—such as coarctation of the aorta or malignant patent ductus arteriosus—and little significance is attached to the thickened left ventricular endocardium. In the heart collection at the Children's Memorial Hospital, diffuse endocardial fibroelastosis was encountered in approximately 10 per cent of all patients with congenital heart disease who were autopsied. The majority of the patients with this finding died within three months after birth, especially when the endocardial fibroelastosis was associated with other anomalies, or when the left atrium and ventricle were so small that they were functionally incapable of handling the pulmonary venous blood flow. Many patients, however, without associated valvular or vascular abnormalities and with a lesser degree of endocardial fibroelastosis, may survive many months, and it is these patients, who were previously described as having "idiopathic hypertrophy," who present the greatest diagnostic problem in the differentiation from other

types of cardiac hypertrophy in infancy. This group of hearts makes up about one third of the specimens with endocardial fibroelastosis.

Pathology. Gross examination reveals an enlarged heart which weighs two to four times the normal weight. The enlargement is predominantly left ventricular. The foramen ovale is either completely closed or has a minute opening, and the endocardium of the left atrium and ventricle has a grayish opaque appearance in contrast to the normal pink color. The left ventricle is dilated and the muscle hypertrophied.

The endocardium, on microscopic examination, is composed of a thick layer of fibrous and elastic tissue. Within this layer and near its junction with the myocardium one may frequently see degenerating cardiac fibers. There is an almost complete absence of cellular infiltrate. If the heart is minutely sectioned, small islands of scar tissue within the myocardium may be noted. The cardiac muscle cells in the left ventricle are severely hypertrophied.

Symptoms, Signs and Laboratory Findings. The onset of symptoms in endocardial fibroelastosis usually occurs about three to six weeks before death; this varies greatly, however, and cases have been reported in which the onset was at birth, while in others symptoms started in the last few days of life. The history usually reveals a variable period of difficult breathing and poor feeding associated with failure to gain weight properly, restlessness and irritability. All symptoms are slowly progressive unless complicated by a respiratory infection, in which case they become rapidly progressive. A family history of congenital heart disease is present in about 20 per cent of the cases.

Physical examination reveals a pale, thin patient who is dyspneic and has a moderate tachycardia. The heart is greatly enlarged, and the heart tones are of good quality. A murmur is usually absent. If, however, the fibroelastosis is severe and there is valvular involvement, a murmur may be noted. There are no diagnostic laboratory findings. Roentgenograms and fluoroscopy of the chest reveal a severe enlargement of all chambers of the heart. Atelectasis of the left lower lobe may be present, owing to the encroachment of the heart on the bronchi and lung. Electrocardiograms usually show a nondescript left ventricular strain pattern. This electrocardiogram, although not diagnostic, is helpful, for the diagnosis of endocardial fibroelastosis may be suspected by eliminating the other causes of cardiac enlargement in infancy, most of which have a fairly characteristic general pattern. This, of course, is not always true, and one occasionally finds borderline electrocardiograms which may be impossible to differentiate.

Treatment. After the diagnosis has been made, treatment consisting in digitalization, oxygen if necessary, prophylaxis against upper respiratory infections and gastroenteritis, vitamins and a nutritious diet may prolong life several months; however, the disease is invariably fatal. The probabil-

ity of curing endocardial fibroelastosis seems, at the present time, unlikely.

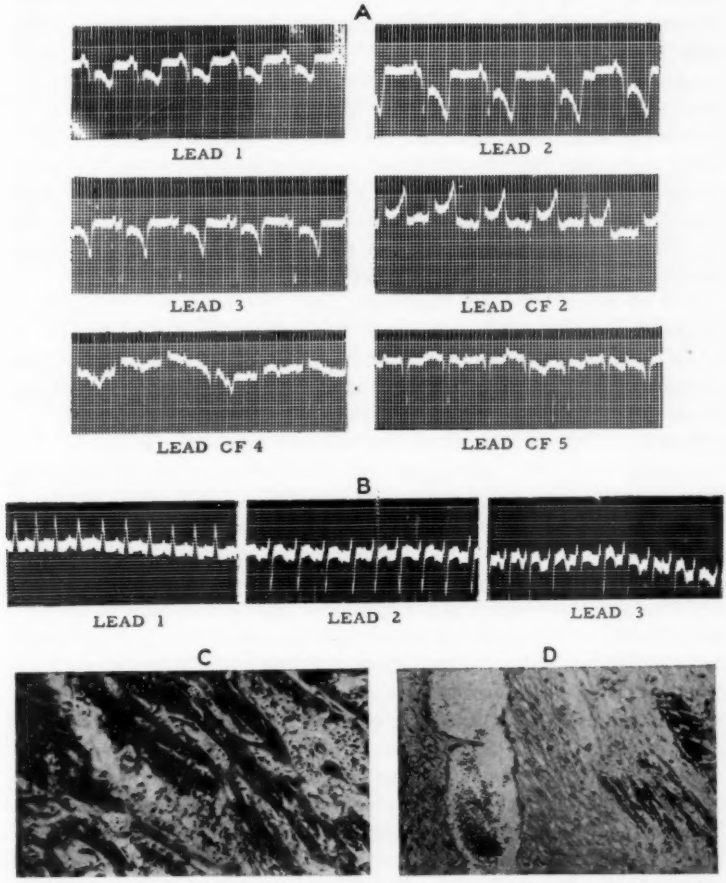

Fig. 92. *A*, Glycogen storage disease. Typical electrocardiogram. *B*, Myocarditis. Slightly atypical electrocardiogram. Note absence of S-T segment changes and isoelectric or inverted T waves in the standard leads. *C*, Acute myocarditis. Note the severe round cell infiltrate and edema of the interstitial tissues of the heart. The muscle cells in this photomicrogram show little evidence of degeneration. (H & E stain. H.P. × 200.) *D*, Aberrant left coronary artery originating from the pulmonary artery. Note calcification and subendothelial sinusoidal dilatation. (H. & E stain. H.P. × 100.)

MYOCARDITIS

It is beyond the scope of this article to discuss the entire problem of myocarditis in infancy, since many of its ramifications are poorly under-

stood and at best remain theoretical in nature. Many kinds of acute infections, such as diphtheria, scarlet fever, mumps, measles, encephalitis, meningitis, poliomyelitis, pneumonia, tuberculosis, and others, may result in myocarditis. In many of these diseases a pure culture of the etiologic agent may be obtained from the myocardium; in other instances the pathogenesis is less clearly demonstrable. In diphtheria, for instance, most pathologists believe that the myocarditis is mainly the result of bacterial toxins, despite the fact that Kirsch[26] was able to culture diphtheria organisms from the myocardium in a high percentage of the patients who died from this disease. The myocardial cultures have been negative in measles, mumps, poliomyelitis and many other diseases, and an allergic response, similar to that seen in rheumatic fever, is usually cited as the mechanism of pathogenesis.

It is of interest to note that myocarditis has been produced experimentally in many different ways. A low potassium, high sodium diet, vitamin deficiency, and sulfonamides may all produce this disease, and the relationships between the acute infection, the antibody response, the treatment, and the metabolic functions of the patient are not clearly understood. Perhaps several of these factors must be abnormal before myocarditis can occur, for certainly this disease is the exception rather than the rule in the majority of acute infections.

The literature contains a number of case reports in which the myocarditis was not preceded or accompanied by an acute infection. This disease may be called Fiedler's, interstitial, idiopathic or isolated myocarditis. In our experience at the Children's Memorial Hospital the presence of myocarditis without a preceding or accompanying acute infection is extremely rare. The etiologic agent of the acute infection may be unknown, as is often the case in an acute gastroenteritis or interstitial pneumonitis; however, the coexistence of myocarditis and acute infection is almost universal.

Pathology. In discussing the pathology and clinical findings in myocarditis, only those patients with significant cardiac hypertrophy will be included, and the cases in which the diagnosis is dependent upon minimal electrocardiographic findings of tachycardia will be eliminated.

Grossly, the heart is enlarged, weighing about two to five times the normal weight. Severe dilatation of the left ventricle is usually present, and cardiac muscle is flabby and of poor consistency. The endocardium frequently has spotty areas of grayish discoloration representing endocardial thickening. The right ventricular changes are less severe.

Microscopic sections reveal a mild to severe interstitial round cell infiltration of lymphocytes, macrophages, plasma cells and occasional eosinophils. The myocardium is severely edematous, and degenerative changes of the cardiac muscle may be noted. Early fibrosis is also seen.

Symptoms, Signs and Laboratory Findings. Acute myocarditis is usu-

ally sudden in onset and occurs, on the average, much later in infancy than the diseases which have been discussed previously. Cases have been reported in the first few weeks of life, however. The onset is often preceded by an acute infection of known etiology, such as measles, mumps, diphtheria or poliomyelitis, or it may be accompanied by an acute infection of unknown etiology, such as an interstitial pneumonitis, acute gastroenteritis or upper respiratory infection. The patient usually has a fever; the pulse rate is much more rapid, however, than the fever would warrant. In severe cases, dyspnea may be present with episodes of cyanosis. The infant is irritable and has a poor appetite. Physical examination may reveal an enlarged heart with poor and distant heart tones. The first heart sound at the apex has a muffed quality, and, on occasion, a gallop rhythm is detectable. In about half the cases there is a hollow-sounding apical systolic murmur. Not infrequently the blood pressure may be decreased. If the myocarditis progresses, the patient may exhibit the findings of failure with an enlarged liver and occasionally even peripheral edema.

In the fatal cases the progression of the disease is usually rapid, ending in but a few days after the onset of symptoms. Occasional cases may be prolonged by the judicious use of oxygen, digitalis and supportive therapy. If the tachycardia responds to the prescribed dosage of digitalis—as occurs in almost 50 per cent of the cases—the prognosis becomes much better.

The laboratory findings frequently reveal a slight leukocytosis with an increase in the number of lymphocytes in the differential count. A slight anemia may be present. Roentgen examination and fluoroscopy of the heart show marked enlargement involving all chambers, but predominantly the left ventricle. Vascularity of the lungs may be slightly increased. The electrocardiogram is usually grossly abnormal. The most characteristic findings are as follows: (1) left heart strain; (2) flattened T waves in all standard leads without much evidence of S-T segment elevation or depression; (3) possible prolongation of P-R interval; (4) tachycardia; (5) low voltage in occasional cases.

Serial electrocardiograms are helpful in following the progress of the disease as well as in making the diagnosis. Changes in the P-R interval, QRS complex and T wave will often occur in a few days.

Treatment. The treatment in myocarditis, no matter what the etiology, resembles the treatment of rheumatic carditis. Early in the disease no specific therapy is necessary, and the patient will usually recover with the use of supportive measures, such as oxygen, vitamins and a nutritious diet. Electrolyte balance must be carefully maintained. If the disease progresses and signs of heart failure appear, digitalization becomes necessary. The use of ACTH or cortisone is of questionable value. We used it in one instance, and the patient has apparently recovered. Whether recovery was due to the therapy or in spite of it is unknown, and judgment must be withheld until a sizable series has been reported.

The prognosis in patients with an enlarged heart due to myocarditis is not good—the mortality rate is about 50 per cent. Those who recover usually have no residuals, and the heart gradually decreases to approximately normal size. Before a better prognosis can be offered these patients, a much clearer understanding of the factors involved in the etiology and pathogenesis of myocarditis must be sought.

SUMMARY

A brief review has been made of the commoner conditions causing cardiac hypertrophy in infancy. A few rare conditions, such as Marfan's syndrome with medial aortic necrosis and polyarteritis nodosa of the heart, may also lead to severe myocardial hypertrophy; they are so infrequently encountered, however, that they are of little clinical significance. An ultimate cure in some cases of cardiac hypertrophy in infancy seems possible, but the majority have a dismal prognosis at present, and there is little hope of improvement in the future.

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THE DIAGNOSIS OF RHEUMATIC FEVER

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Rheumatic fever is a disease which is identified by the clinical manifestations of associated pathology. In spite of auxiliary laboratory procedures introduced in the hope that a specific serologic or biochemical test could be discovered, this hope has not been realized. Many of the problems related to rheumatic fever will be solved with the advent of a specific diagnostic procedure.

The definition of rheumatic fever as a disease with no known pathogenesis, no specific diagnosis and no specific treatment must be qualified. Though the etiologic mechanism is not understood, the relation of the disease to beta-hemolytic streptococcus infection is almost universally acknowledged. Even in the absence of a specific diagnostic test many of the manifestations of the disease are readily identified, and others can be suspected. And there is a specific treatment for the acute arthritic manifestation of the disease, for an acute arthritis that does not respond to 30 mg. per 100 cc. blood level of salicylate almost surely is not the acute arthritis of rheumatic fever. Hormone therapy suppresses remarkably some of the more serious manifestations of the disease.

From the standpoint of diagnosis, the disease is best regarded as a systemic disease which affects several organ systems, but does so unevenly and without a constant pattern even in a single system. Diagnosis rests upon identification of nonspecific systemic aspects of infection in association with more specific manifestations related to specific organ systems. But the diagnosis cannot be made on the basis of evidence of systemic infection alone. The areas in which diagnostic manifestations occur are (1) the cardiovascular system, (2) skeletal system, (3) central nervous system, and (4) skin. Most of these manifestations are well known.

Perhaps insufficient emphasis has been given to the rash of rheumatic fever, the most common variety of which is specifically diagnostic. This is the *erythema annulare*, which is as diagnostic of rheumatic fever as the eruptions of rubeola or varicella are of those diseases. Though usually

accepted as a rheumatic phenomenon when the disease has been diagnosed by more flagrant manifestations, even one or two such annular eruptions occurring transiently are diagnostic. The laity identified the rash as evidence of a specific disease by the term "horseshoe fever," since the annularity of the lesion is frequently interrupted, and it appears as small horseshoes rather than rings. Variations also occur, especially a larger, more irregular type. The eruption is not suppressed by salicylates or cortisone, it may be present without any laboratory evidence of systemic infection, and it may occur intermittently as an isolated manifestation of rheumatic fever for many years, especially during periods of warmth or excitement. The proper disposition of the patient in this event is difficult.

Rheumatic nodules are subcutaneous rather than cutaneous manifestations, but they are most readily identified by inspection. Though they usually occur during obvious rheumatic fever, rarely these will appear without other evidence of the disease. Nodules alone cannot be identified adequately as rheumatic in the absence of a concurrent diagnosis, and require biopsy for identification of their rheumatic nature.

Some have attempted to standardize the criteria for diagnosis of rheumatic fever by grading clinical or laboratory manifestations into major and minor categories[1–5] and using some pattern of association for diagnosis. Major manifestations are diagnostic, as carditis, arthritis, chorea and subcutaneous nodules; minor manifestations are those of nonspecific systemic infection, as fever, leukocytosis, elevated sedimentation rate or abdominal pain. But these latter manifestations are simulated by numerous childhood illnesses or complaints and are often evidence of nonrheumatic systemic infection. Epistaxis is so common as a childhood complaint that it may be questioned as suggestive of rheumatic fever. Regardless of the method of approach to diagnosis, the fact remains that the patient either has rheumatic fever or does not have it, and at a specific time frequently it is impossible to decide.

The diagnosis of rheumatic fever is not a problem when the typical acute disease occurs. Diagnostic problems are related to borderline equivocal situations when suggestive but not diagnostic features are present. Rheumatic fever has standard manifestations, course and response to treatment, and although these have many variations, they occur within limits of minimum and maximum extremes. Atypical rheumatic disease usually is something else: rheumatoid arthritis, lupus erythematosis, periarteritis nodosa or dermatomyositis.

CLINICAL CRITERIA

Because of preoccupation with identification of positive diagnostic features of the disease, insufficient attention has been given to the diag-

nosis of pseudorheumatism, a term which may be applied to miscellaneous historical, physical or laboratory findings which alone or in combination simulate manifestations of rheumatic fever. But this functional disorder often is easier to identify than the disease itself, and it is important to distinguish among those who have, or are suspected of having, rheumatic fever, and those who do not, and thus restricting the problem of diagnosis.

Clinical functional disorders simulating complaints or findings suggestive of rheumatic fever have several aspects. Most of these are of frequent occurrence, some are ubiquitous, and all are characterized as nonrheumatic. But just as chorea may occur in a child with tics, rheumatic fever may develop in the presence of common pseudorheumatic manifestations.

Fever

A frequent complaint relative to the diagnosis of rheumatic fever is fever. After one of the miscellaneous childhood infections the temperature is taken daily as an index of recovery. The temperature is discovered to be about 1 degree above the accepted normal value at least once daily. This is then considered fever, and if even remote auxiliary evidence of rheumatic fever is found, the diagnosis may be seriously considered. The care of children requires repeated emphasis that the normal child rarely has temperatures consistently below 98.6° F., and the majority of children have temperatures sometime during the day of over 99° F. Rarely this will rise to 100° F. daily over a prolonged period of observation without any demonstrable evidence of disease. Such 99.6° F. temperatures should not be coupled with the presence of a functional murmur or an equivocal elevation of sedimentation rate to substantiate the diagnosis of rheumatic fever, and this association appears to represent the most important area of overdiagnosis. In medicine, as in law, the patient is innocent until proved guilty, and the diagnosis must rest upon more direct objective evidence than an association of the upper limit of normal variation in temperature, cardiac sounds or hemopoietic values.

Leg Pain

Acute arthritis in a child, associated with swelling and tenderness, is surely rheumatic in origin until proved otherwise, and usually is an unequivocal basis for the diagnosis of rheumatic fever. Of greater concern is subjective complaint of pain or discomfort in extremities, since the physician must choose between overdiagnosis and institution of a rheumatic convalescent regimen and underdiagnosis with perhaps aggravation of potential cardiac involvement. Fortunately, nonrheumatic leg pains have a fairly characteristic pattern, and the history is so typical and

repetitive from patient to patient that rheumatic fever can be excluded. This exclusion by history rests on the assumption that rheumatic pain is arthritic and is related to localization in joints.

Nonrheumatic leg pains in children are common and are perhaps what once were referred to as "growing pains." Such pains are infrequent during daily activity. Most commonly complaint begins after going to bed, and often discomfort in the legs awakens the child from sleep. The pain is restricted to muscle groups in the thigh and calf, and frequently there is complaint of distress in the ligaments behind the knee. This discomfort disappears with massage, heat or aspirin. Most frequently the mother massages the complaining muscle, sleep is restored, and the child continues play the next day without complaint during extraordinary physical activity. These complaints are uniform in history, in therapy and in their nocturnal onset. They are nonrheumatic.

Quite different are complaints related to joints themselves or to transient pains in the upper extremities. Diurnal joint pains worsened by activity without objective signs of local tenderness are more difficult to evaluate, and contributory evidence of rheumatic fever must be rigorously excluded before they can be considered functional in origin.

Murmurs and Other Cardiovascular Phenomena

Since there are no specific tests for the systemic aspects of rheumatic infection, diagnosis rests upon specific rheumatic manifestations usually apparent in organ systems. The most important organ system affected is the cardiovascular system.

In the presence of systemic evidence of nonspecific infection and suggestive rheumatic symptoms, the absence of cardiac murmurs of valvular origin cannot exclude the diagnosis of rheumatic fever. Considerable heart disease is required to produce an unequivocal diagnostic murmur, and acute rheumatic arthritis is not always associated with clinical evidence of heart disease. It can be assumed that subclinical heart disease is present, however; if this assumption is correct, the future of such patients is protected by at least a reasonable period of bed rest.

Examination of the heart separates two extremes, the average typical nonrheumatic heart in childhood, which frequently includes a moderately loud functional murmur, and murmurs which are clearly valvular in origin. An intermediate group includes those children with murmurs which cannot be categorized clearly, which are abnormal for functional murmurs, but which are not readily identified as acquired valvular murmurs.

Functional Murmurs. The typical functional murmur in childhood has some characteristics which identify it and clearly separate it from the murmur of rheumatic heart disease. It has a more or less specific location,

radiation and variability of intensity either spontaneously or by simple maneuver. Superficially, this functional murmur appears to have its maximum intensity in the second left interspace, but usually it can be heard with diminishing intensity along the left sternal border. However, if routine examination of the heart includes routine examination of the subclavicular and supraclavicular areas, and if any murmur heard is followed up the neck, it will be clear that these murmurs have their maximum intensity in the right and rarely the left supraclavicular area, and that they radiate from this area of maximum intensity downward along the left sternal border.

The precordial systolic murmur is merely an attenuated remnant of the supraclavicular murmur; the greater the distance from the primary site of origin, the less intense it becomes. But it may extend, although with diminishing intensity, to the apex. Because of the sigmoid shape of the pattern of radiation, like an **S** lying on its side, it is sometimes referred to as the "*S* murmur." However, *F* for functional would be a better appellation.

The murmurs in the neck appear to be of two varieties, those related to the venous hum, which has a more or less continuous quality and is usually assumed, although not proved, to be of venous origin, and those purely systolic in time which are of arterial origin.[6] That the precordial murmur is clearly extracardiac in origin can be demonstrated by its disappearance when the neck murmur lessens or disappears by local pressure on the neck or by change in position of the head. Organic cardiac murmurs are not so easily varied by manipulation of relatively minor vessels. Many of the parasternal murmurs disappear when the patient is asked to raise the head. This maneuver, in children, is usually accompanied by diminution or disappearance of the neck murmur and almost simultaneous disappearance of the parasternal murmur, and both recur shortly after the head again becomes recumbent. The presumed cardiac murmur is therefore identified as extracardiac in origin and functional in nature. Auscultation of the neck is an intrinsic part of examination of the heart in children, and the intensity of murmurs in the neck is often surprising. Indeed, the murmur in the neck is sometimes associated with a thrill in the same area, and the diagnosis of a congenital arteriovenous fistula must be considered.

This is the usual murmur of childhood and, when associated with functional nocturnal leg pains and equivocal evidence of systemic infection, gives a superficial resemblance to rheumatic infection. But analysis of the extremity pain, and closer inspection of the site of maximum intensity and the radiation of the murmur from an extracardiac area to the precordium rather than the reverse, clearly identified the cardiac problem as nonrheumatic. Though the murmur and the typical radiation and variation with maneuver of the neck or head can be followed by phono-

cardiogram, this is not necessary, and bedside examination with the stethoscope is adequate.

Organic Murmurs. In contrast to the cardiac murmur clearly nonrheumatic in origin, murmurs related to rheumatic carditis are intracardiac and valvular in origin. These vary from unmistakable auscultatory evidence of valvular disease to more subtle, less intense murmurs which nevertheless are diagnostic. The prototype of the rheumatic murmur and the one most frequently encountered is the murmur of mitral insufficiency. It is a systolic murmur which has its maximum intensity at the apical area. Such a separate murmur at the apex is, in the absence of severe anemia or cardiac enlargement from other cause, diagnostic of the presence of rheumatic heart disease. Since functional murmurs occur commonly in younger children, this murmur must be sought for in addition to the functional murmur if the presence of rheumatic fever and rheumatic heart disease is being considered. Even a short grade 2 systolic murmur localized in the apical area is satisfactory evidence of this disease.

A number of equivocal situations will be encountered when the parasternal murmur is louder than usual and not sharply circumscribed to this area and continues to be heard, although less intensely, when the apical area is reached with the exploring stethoscope. It is sometimes impossible to decide by auscultation alone in this situation whether mitral rheumatic disease is present or whether there is an associated or isolated acyanotic congenital defect.

A simple screening test is available which distinguishes the origin of murmurs which arise from acyanotic congenital heart disease and identifies them as nonrheumatic in origin. This is the dye dilution curve. Intravenous injection of Evans blue dye in conjunction with a recording oximeter results in abnormal curves in the presence of shunting lesions associated with congenital heart disease.[7] They do not distinguish isolated obstructive lesions,[8] but these are uncommon. But dye dilution curves differentiate rheumatic heart disease from the predominant lesions of acyanotic congenital heart disease, and are of great value in equivocal situations, as illustrated in Figure 93.

A murmur in diastole occurs at the apex in situations other than in relation to rheumatic valvular disease, but only if organic heart disease is present. Separate systolic and diastolic murmurs appear at the apex regularly in congenital heart disease if this is associated with considerable cardiac enlargement, especially of the left ventricle. Such murmurs, especially diastolic, are commonly associated with intracardiac or extracardiac arteriovenous shunts when pulmonary blood flow and consequently return flow to the left heart are augmented. When this augmented flow is considerable, excessive flow through an undiseased mitral valve produces a diastolic murmur of relative mitral stenosis in the same way that the murmur of mitral stenosis is produced by restriction of normal flow. Such

apical murmurs associated with known congenital heart disease are not evidence of superimposed rheumatic heart disease, but are a variety of functional murmur associated with augmented flow through the left heart or dilatation of the left ventricle. These are demonstrated most readily in instances of patent ductus arteriosus with considerable aortic pulmonary artery shunt. The apical murmurs will be absent when the stethoscope can be placed on the chest after closure of the ductus.

Rarely the diastolic murmur of *aortic regurgitation* will be confused with that of pulmonary insufficiency, but fluoroscopy will identify the large pulmonary artery associated with high pressure and regurgitation through this valve, absent in simple aortic regurgitation. The diagnosis of

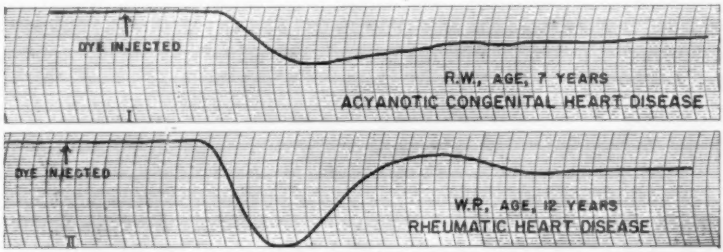

Fig. 93. Dye dilution curves. *Upper,* The dye dilution curve is typical of a left-to-right shunt of considerable severity in acyanotic congenital heart disease. *Lower,* History suggestive of rheumatic fever, but a grade 3 systolic murmur was maximum at the third and fourth left interspaces and resembled the murmur of an interventricular septal defect. The dye diluation curve has a normal contour, and there is no evidence of a left-to-right shunt. Congenital heart disease which includes any shunting lesion can be excluded from the differential diagnosis.

aortic regurgitation does not require auxiliary peripheral signs, since these are present only with considerable cardiac enlargement and marked regurgitation into the left ventricle. The diagnosis rests upon the characteristic murmur, which never disappears or diminishes in intensity even when faintly audible. It gradually becomes more evident.

Cardiac Arrhythmias. Circulatory disturbances sometimes raising the suspicion of rheumatic fever are *arrhythmias.* This problem varies from simple tachycardia to more complicated paroxysmal arrhythmias. Certainly the frank rheumatic tends to have tachycardia if there is a considerable degree of carditis, although bradycardia may occasionally occur. The problem of diagnosis therefore does not depend so much upon heart rate as an index of convalescence from known rheumatic carditis, as upon tachycardia alone in the presence of other equivocal evidence of rheumatic fever as a useful auxiliary sign of rheumatic infection.

Sinus tachycardia is common in children, and the limits of normal variation of heart rate, especially with exercise, are not too well identified. Patients with heart rates consistently over 100 may be followed for years

without the appearance of acceptable evidence of rheumatic fever. Increased heart rate alone requires a review of hyperthyroidism, occasional electrocardiograms and repeated laboratory examinations for evidence of systemic infection. But tachycardia alone without substantiating evidence of rheumatic fever is an inadequate basis for institution of a rheumatic convalescent regimen.

A simple arrhythmia such as *extrasystoles* occurring alone is not evidence of rheumatic infection. These are common in normal infants and children and occur at rest and disappear with exercise. Of greater importance is this arrhythmia increasing with exercise; in this situation heart disease of some variety probably exists, and a persistent endeavor should be made to identify this, since it may be rheumatic fever. Again, such disease may be present with sedimentation rates within the limits of normal, and the problem often becomes one solved only by the development of some specific diagnostic feature.

Paroxysmal tachycardias, either auricular or bizarre chaotic rhythms, most often occur in the absence of identifiable organic heart disease and otherwise are a manifestation of obvious severe rheumatic or congenital heart disease.

Precordial Distress. Often a patient is seen for the complaint of precordial pain, and the parent, perhaps relating this to adult friends or relatives with angina pectoris, is concerned with the possibility of this as a symptom of heart disease. It is true that precordial pain or poorly described distress in this region frequently accompanies the onset of rheumatic pancarditis, but this can be identified by auxiliary signs. Precordial distress as an isolated symptom does not suggest heart disease in children. Most of these complaints are related to intercostal or pleural pain, and the cause usually is not identifiable. If the pain seems definitely related to exercise, an electrocardiogram is desirable, and rarely an electrocardiogram during exercise will indicate an organic basis for the complaint.

Electrocardiographic Evidence. Opinions concerning the usefulness of the electrocardiogram as an adjunct to diagnosis of rheumatic fever vary, and depend to some extent upon opinion as to the specificity of conduction changes in children. Single tracings with borderline abnormalities must be approached with caution. The normal variation of P-R interval is perhaps greater than indicated by reference to tables. Graybiel[9] found instances of delayed conduction in healthy young adults, and in these instances it is likely that this abnormality was present in childhood. More significant are changing values of the P-R intervals, which in the absence of other toxic or infectious processes probably represent rheumatic infection.

The diagnostic value of the Q-T interval, as introduced by Taran and Szilagyi,[10] has been reviewed by Craige and associates,[11] and it seems

likely that this is also subject to influences other than rheumatic and that as an isolated finding it is not specific as a diagnostic criterion.

This is not to say that during rheumatic carditis serial electrocardiograms do not show abnormalities. The problem is the position of the electrocardiogram as a diagnostic aid when clinical evidence is insufficiently diagnostic. Suggestive evidence of the diagnosis may be obtained on a single tracing, and more convincing evidence on serial tracings. But borderline abnormalities of the electrocardiogram, like borderline abnormalities of the sedimentation rate or suggestive clinical history or organ system manifestations, are insufficient to stigmatize the child with a casual diagnosis of rheumatic fever.

Fidgets, Tics and Chorea

All children are fidgety. This results from a short span of attention, abundant energy and sometimes emotional tensions. If the threshold of annoyance in the parent or teacher is low, the children are classified as nervous. Almost all young children, if asked to sit with arms extended before them, will have some quick movements of muscle groups around the shoulder or torso. These are intermittent and nonrepetitive. They represent neither tics nor chorea. They are normal. Tics are usually quick repetitive muscle spasms of facial muscles. They may be more complicated, and involve coordinated movements of a variety of muscle groups. These are neither choreic nor prechoreic manifestations.

Central nervous system manifestations of rheumatic infection are grouped under the general title of *Sydenham's chorea*. The fact that choreiform movements may occur without systemic evidence of infection does not mean that there are two kinds of chorea, rheumatic and nonrheumatic, just as the presence of mitral insufficiency without evidence of systemic infection does not mean that this, therefore, is not rheumatic in origin. Chorea may be accompanied by other stigmata of rheumatic fever, either clinical or laboratory, but often is not. This is interpreted as indicating that the pathology is restricted to the central nervous system, and that the systemic infection cannot be identified by the crude laboratory procedures now available.

It is believed that the essential pathology of chorea lies in the cortex.[16, 17] There are other opinions.[12–15] The positive Babinski occasionally seen on the most affected side is compatible with this thesis. With organic cortical disturbance various psychic manifestations of chorea become apparent and concomitant. But these do not mean that chorea is psychogenic in etiology, regardless of apparent psychiatric aspects of the disease which arise or are accentuated by cortical pathology. Chorea is a rheumatic manifestation that is specifically diagnostic. Like acute rheu-

matic fever, chorea in a flagrant form is readily recognized. Minor manifestations are sometimes confused with *habit spasms* or *tics*. But these latter are usually so characteristic, so repetitive in contrast to the irresponsible nonrepetitive movements of chorea that differentiation is seldom difficult.

Since minor tics are common in children, difficulty may arise when mild choreiform movements are associated with habit spasm. Care must be taken that the choreic manifestations are not dismissed as a variety of tics, or that tics are not overdiagnosed as representing more severe chorea than is present. The situation is similar to that when a rheumatic mitral apical murmur is present in addition to the common functional murmur. As in rheumatic fever in general, the diagnosis of chorea is a clinical diagnosis, and there are no specific laboratory diagnostic criteria. Laboratory evidence of systemic infection and auxiliary clinical evidence of rheumatic fever may never appear during or subsequent to the disease.

Other central nervous system manifestations of rheumatic fever occur during the course of severe disease, and are usually unmistakable as complications rather than as diagnostic phenomena. Such are the cerebrovascular accidents, related to arteritis, embolization during subacute bacterial endocarditis or auricular fibrillation and the rare overwhelming rheumatic encephalitis.

Friedreich's ataxia in its early stages may be confused with chorea, and it is sometimes forgotten that an apical diastolic murmur may be present in this disease.[18]

Laboratory Examinations

It is, of course, impossible to classify objective laboratory information as organic or functional, yet apparent abnormalities in the absence of disease are analogous to other functional disturbances, subjective or objective. Thus hematologic values may be misleading.

Mild to moderate degrees of *hypochromic anemia* are so common in children that those related to disease and those that reflect previous dietary habits are not easily distinguished. *Leukocytosis* may be slight or pronounced in rheumatic fever identified on other evidence, but in temperate zones where upper respiratory infection and sinusitis may be chronic, leukocyte values of 7000 to 10,000 cannot alone be considered of diagnostic value. These values may be elevated when the sedimentation rate is normal, and when the elevation is gross are contributory evidence in situations otherwise equivocal.

The *sedimentation rate* of red blood cells is both the most useful and the most misleading element in auxiliary laboratory determinations relative to the diagnosis of rheumatic fever. This is a reasonably delicate test

of systemic infection, nonspecific for rheumatic fever and affected by a variety of factors, some related to infection and some to serum protein disturbance and tissue changes nonrheumatic in nature. It is therefore useful in ascertaining the presence of rheumatic disease if this is present above an as yet unidentified level. But many clinical and pathologic reports indicate that rheumatic activity may be evident in the presence of a normal sedimentation rate. The determination is too sensitive to nondescript nonrheumatic factors and not sensitive enough for equivocal rheumatic problems. If all children who have leg pains, temperatures of 99.4° F. and sedimentation rates of 22 mm. per hour were considered to have rheumatic fever, a great injustice would be done. Even in the presence of known rheumatic fever or heart disease, the sedimentation rate must be considered indicative of active rheumatic infection only when greater than perhaps 6 on a 12-inch rule; below values usually considered normal, slumbering low grade rheumatic activity continues.

It is not possible to use 15 mm. per hour as the upper limit of the normal sedimentation rate in children in the diagnosis of rheumatic fever. Though values below this are reassuring in diagnosis or evaluation of the course of the disease, rates of 15 to 20 mm. are encountered frequently in nonrheumatic children, and in obese children, especially females, the value may be higher. The sedimentation rate at these levels can be applied to the problem of diagnosis only in relation to other information of diagnostic value when borderline equivocal situations are reviewed.

Quite different is the import of rates above 30 mm. per hour. Scarcely any other disease which might be confused with rheumatic fever gives such high or sustained elevation. But with gross elevation of the rate of erythrocyte sedimentation the diagnosis is usually already apparent.

The status of correction of rates of red blood cell sedimentation against hematocrit values is not clear. Values uncorrected in this manner are too high, while values so corrected may be too low if the hematocrit is grossly abnormal.

Because of the nonspecificity of the sedimentation rate, numerous other laboratory procedures have been introduced as aids to diagnosis. These have been reviewed recently by Good.[19] At the present time they have not proved to be more sensitive or more specific than the sedimentation rate and are not immediately useful in clinical practice. Perhaps an exception to this is the determination of the *antistreptolysin O titer*. Though probably nonspecific in relation to rheumatic fever,[20] it evaluates the presence of streptococcal infection, and low titers indicate the absence of recent infectious episodes which are a precipitating factor in the development of rheumatic fever. But high titers are indicative only of recent infection and do not determine whether this has been followed by rheumatic fever.

CONCLUSION

There are two essentials in the diagnosis of rheumatic fever. The first is familiarity with children and the components of motor and emotional behavior, the sights and sounds of health, and the more concrete normal variations of cardiovascular and blood findings. The second is familiarity with rheumatic fever, the gross manifestations and the subtle, transient masquerade of symptoms and signs. Most errors in diagnosis are related to some aspect of these essentials. Knowledge in the second essential can be accelerated by study of the literature. But current reading cannot supplant examination of Cheadle's,[21] Coombs',[22] Findlay's[23] and Osler's[24] works on the subject.

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THE TREATMENT AND PREVENTION OF RHEUMATIC FEVER*

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The patient with acute rheumatic fever or the parents of these patients are immediately concerned with the relief of such symptoms as pain in the joints, fever, chest pain and dyspnea. The physician, in contrast, is more concerned with the problem of preventing damage to the heart, for it is this aspect of the disease which results in death either during the acute phase or during the subsequent years because of chronic deformity of the valves.

The relief of the immediate symptoms is easily obtained by the use of aspirin, ACTH or cortisone. The prevention of myocardial and valvular heart disease is more of a challenge, and to obtain a successful outcome continued interest by both the physician and the patient is required. That the challenge should be accepted by both is well established, since methods are now available which, if properly used, will result in a great reduction in the incidence of acute rheumatic fever and rheumatic valvular heart disease. It is estimated that at least 50 per cent of the total cases of rheumatic heart disease are now preventable.

The problem of effecting this reduction in the incidence of rheumatic fever and rheumatic heart disease is a problem in education of the profession and the public. Since contact with the public is through the physician, it becomes necessary for him to define his duties in this pro-

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gram. The first step is a thorough understanding of the natural history of rheumatic fever and the vulnerable points that may be attacked.

NATURAL HISTORY OF RHEUMATIC FEVER

Rheumatic fever is usually, if not invariably, preceded by an infection with group A streptococci. Most of the epidemiologic features of rheumatic fever are those of group A streptococcal infections. The importance of age, sex and geography in the occurrence of rheumatic fever appears to be related to the effect of such factors on the occurrence of streptococcal infections in general, since once such infections occur, the attack rate of rheumatic fever is relatively constant. Advances in our knowledge concerning the prevention of these infections will eventually solve many of the problems of rheumatic heart disease.

Of all persons infected by group A streptococci, approximately 80 per cent exhibit some symptoms of an acute respiratory disease. Untreated, the acute phase subsides in a few days and the patient again feels well. Approximately 3 per cent of such patients will, however, suffer the nonsuppurative complication, rheumatic fever. The first rheumatic symptoms may occur during the acute streptococcal infection itself or may develop twenty to forty days later. In general, however, the majority of patients with rheumatic fever have symptoms between the tenth and twenty-fifth days after the onset of the respiratory disease.

The attack of rheumatic fever may be so mild that it goes unrecognized, or it may be severe and terminate in death. Fortunately, the latter outcome is rare today; the former is common. Of those patients who show some symptoms of rheumatic fever after a streptococcal infection, it is estimated that approximately 50 to 70 per cent will later have rheumatic valvular heart disease. Many, moreover, will show evidence of heart involvement during the acute stage, but it is difficult to predict which patients will subsequently show permanent valvular damage. Most patients with acute rheumatic fever recover from the acute symptoms within two months, and only a few exhibit chronic recurring disease.

Unfortunately, after recovery from the attack of rheumatic fever the patient is susceptible to recurrences. These recurrences again are caused by infection with group A streptococci. For the first few years after an attack the recurrence rate after streptococcal infections is high, probably over 50 per cent. Thereafter, if the patients remain free of such infections, the recurrence rate declines, although the attack rate among this population remains greater than among the general population for years.

At present the physician may attack the primary problem of rheumatic heart disease at several points, some of which are more vulnerable than others. The initial attack of rheumatic fever may be prevented in many instances, thus preventing rheumatic heart disease. Once rheu-

matic fever develops, the present methods of therapy are not considered to be ideal, although some modes of therapy may possibly alter to a minor extent the degree of cardiac damage. Finally, in rheumatic patients it is possible to prevent most recurrences, thus minimizing eventual valvular disease.

PREVENTION OF INITIAL ATTACKS OF RHEUMATIC FEVER

Ideally, any method which will prevent streptococcal respiratory infections should prevent rheumatic fever. Such infections are prone to occur in the northern states during the winter months. They are especially frequent in young children. Spread of such infections appears to be due primarily to intimate contact. There is little evidence that dust, contaminated articles such as clothing and toys, and droplet nuclei are important methods of spread. Thus it could be anticipated that the use of aerosols, ultraviolet light and dust-settling compounds might have little effect on the spread of streptococcal infections; indeed, such methods have failed to alter infection rates appreciably.

Other methods of control have been attempted. Physicians have removed tonsils, but such a procedure has not diminished the incidence of rheumatic fever, nor is there evidence that the incidence of streptococcal infections is decreased. Vaccines have been used without success. Since immunity is type-specific, it is doubtful whether vaccines which do not contain M protein from several serologic types of streptococci will be effective. To date, purified M protein has not been available for immunization.

Streptococcal infections may be prevented by continuous prophylaxis with one of the sulfonamide compounds or penicillin. This procedure, however, is not applicable to the general population. Under unusual circumstances it might be used in small, compact population groups, such as boarding schools and nursing homes, during periods of high rates of streptococcal disease.

The most effective method for the prevention of initial attacks of rheumatic fever is treatment of the streptococcal infection. *Adequate* therapy of acute streptococcal infection not only prevents the development of the clinical symptoms of rheumatic fever, but also prevents the electrocardiographic evidence of myocardial involvement. Presumably, therefore, rheumatic carditis is prevented.

The diagnosis of streptococcal infections is not difficult in most instances. Characteristically the patient has a sore throat associated with such constitutional symptoms as feverishness, chilliness, anorexia and headache. The sore throat is not just "dry" and "irritated"; rather, the patient complains of pain or soreness upon swallowing. This pain is referred to the tonsillar regions and the lymph nodes draining these areas.

Occasionally, when rash is evident, the diagnosis is scarlet fever. Inspection of the throat shows the tonsils, lymphoid tissues of the oropharynx and the soft palate to be *diffusely red* and somewhat edematous. Careful examination usually reveals discrete or confluent areas of exudate on the tonsils or small spots of exudate on the lymphoid tissues of the oropharynx. This exudate should not be confused with mucus or postnasal discharge. Of considerable diagnostic importance is the presence of enlarged and tender cervical lymph nodes.

In those patients in whom there is some doubt as to the streptococcal etiology of the disease, the total leukocyte count and a throat culture are exceedingly helpful. In the patient with a streptococcal infection the leukocyte count is elevated, usually above 12,000. In nonstreptococcal exudative tonsillitis which is observed in children and adults the leukocyte count is usually normal. Throat cultures, when facilities are available, will assist greatly in establishing the diagnosis. The isolation of large numbers of beta-hemolytic streptococci usually indicates infection with this organism.

Once the patient is thought to have a streptococcal infection, treatment should be instituted immediately. A number of antibacterial agents are available which will relieve symptoms and prevent suppurative complications, but primary consideration should be given to the prevention of rheumatic heart disease. Present evidence indicates that the drug and dosage given should be determined by the effect produced on the streptococcus. *Eradication* of this organism is *essential* if the complication of rheumatic fever is to be prevented. This may be most readily accomplished by giving penicillin. The preferred schedule in children is either 300,000 to 600,000 units of procaine penicillin in oil containing 2 per cent aluminum monostearate every two to three days for three injections, or a single injection of 600,000 units of Bicillin (N, N^1-dibenzyl-ethylenediamine penicillin). If penicillin cannot be given, Aureomycin or Terramycin should be administered in full doses for a period of *at least eight days*. In all patients a follow-up examination should be made between twenty and thirty days after the onset of the infection to make certain that symptoms or signs of rheumatic fever have not occurred.

TREATMENT OF THE ACUTE ATTACK OF RHEUMATIC FEVER

The effects of aspirin, cortisone or ACTH on the symptoms and signs associated with an attack of acute rheumatic fever are best presented by example. For this purpose we have selected 3 patients from a group of 234 patients who received one of these compounds during a study* of the comparative effects of these drugs on rheumatic fever.[1]

* The study is a part of the cooperative investigation being conducted by the American Heart Association.

Acute Rheumatic Fever Treated with Aspirin

A 19 year old white youth entered the hospital on June 7, 1952, complaining of pain and stiffness in both knees, shoulders and wrists of 24 hours' duration. Past history revealed that at the age of 6 the patient had been confined in bed for 5 months because of joint pains.

On admission the patient was noted to have polyarthritis involving both knees, wrists and shoulders, a rectal temperature of 103° F. and an elevated erythrocyte sedimentation rate. Examination of the heart revealed no murmurs or pericardial friction rubs. The electrocardiogram was normal. Although he denied having symptoms of a preceding streptococcal pharyngitis, a throat culture on admission was positive for group A streptococci, type 5, and the serum antistreptolysin titer was 400 units.

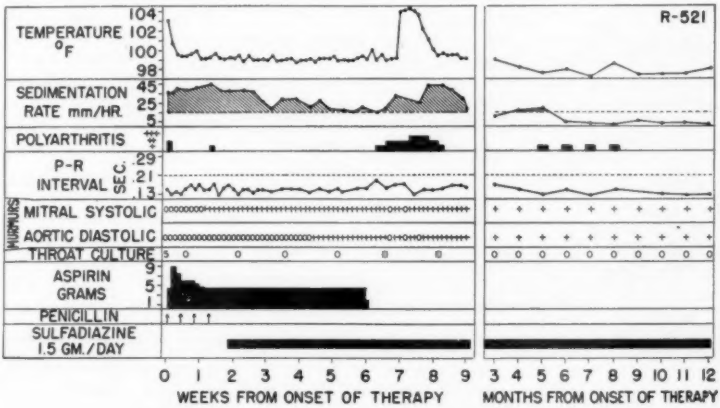

Fig. 94. Acute rheumatic fever treated with aspirin.

On the third day of illness aspirin therapy was instituted for 6 weeks in amounts shown in Figure 94. Procaine penicillin in oil, 600,000 units, was given in order to eradicate the streptococcal carrier state. After this the patient received sulfadiazine prophylaxis for the remainder of the observation period. He remained at bed rest for 12 weeks, and was then allowed gradually increasing activity.

Within 24 hours from the onset of treatment the joint pain and tenderness disappeared, and by the second day of treatment his temperature returned to normal. The erythrocyte sedimentation rate fell slowly over the 6 week treatment period. On the eighth day of treatment a medium-pitched, blowing, apical systolic murmur of moderate intensity was heard in all positions. On the thirty-first day of therapy a loud, high-pitched, blowing aortic diastolic murmur was elicited for the first time.

After the cessation of therapy he had marked polyarthritis, high fever and a further elevation of the erythrocyte sedimentation rate. The polyarthritis and fever subsided within 2 weeks without further therapy, but the erythrocyte sedimentation rate remained slightly elevated until the sixth month. During the follow-up period occasional polyarthralgia was noted, but at no time were any of his joints tender. Both the mitral systolic murmur and the aortic diastolic murmur remained unchanged.

Acute Rheumatic Fever Treated with Cortisone

An 18 year old white youth entered the hospital on August 30, 1951, complaining of migratory pain, stiffness and swelling in both ankles, knees, hips, shoulders, wrists,

elbows and feet for one month. Approximately one month before the onset of joint symptoms the patient had a mild sore throat, but did not seek medical care. Past history revealed no evidence of rheumatic manifestations in the patient or members of his family.

On admission the patient was febrile and had polyarthritis involving both shoulders, wrists, hips, knees, ankles and feet. Examination of the heart revealed no murmurs or pericardial friction rubs. An elevated erythrocyte sedimentation rate (23 mm. per hour, Wintrobe, uncorrected) was present. The electrocardiogram showed an incomplete atrioventricular block with a P-R interval of 0.26 second. Group A streptococci were not isolated from a culture of the throat, but his antistreptolysin titer was 833 units.

On the thirty-second day of his illness cortisone therapy was given once daily by injection in the doses shown in Figure 95. Cortisone was given for 6 weeks, during

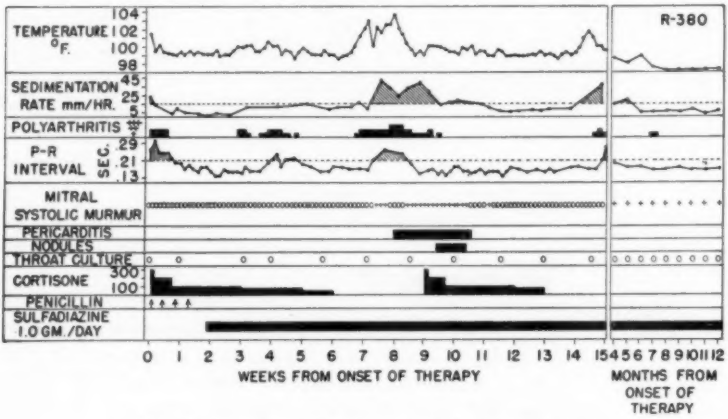

Fig. 95. Acute rheumatic fever treated with cortisone.

which time he received potassium chloride, 1 gm. 3 times daily. For the first 4 weeks of treatment the diet contained less than 2 gm. of sodium chloride per day. Procaine penicillin oil, 600,000 units, was given every third day for a total of 4 injections. After this the patient received sulfadiazine prophylaxis. He remained at bed rest for 4 months, and was then allowed gradually increasing activity.

By the third day of treatment the temperature returned to normal, and by the fourth day the joint pain and tenderness disappeared. The erythrocyte sedimentation rate fell rapidly to within normal range. The P-R interval returned to normal on the sixth day of treatment. At the end of the third week of therapy, when the dose of cortisone was reduced from 100 mg. to 75 mg. per day, polyarthritis and a low grade fever reappeared, accompanied by a prolongation of the P-R interval. The erythrocyte sedimentation rate increased slightly. These abnormalities disappeared within 2 weeks without increasing the daily dose of cortisone.

After the cessation of therapy the patient again had polyarthritis, high fever, an elevated erythrocyte sedimentation rate and a prolonged P-R interval. A pericardial friction rub and a medium-pitched, apical systolic murmur of moderate intensity were heard for the first time. There was a 10 per cent increase in the transverse diameter of the heart as measured on the teleroentgenogram. The patient exhibited no symptoms or signs of congestive heart failure. Treatment with cortisone was reinstituted for a 4 week period. The pericardial friction rub disappeared 10 days after the onset of therapy, and the heart returned to normal size. The mitral systolic mumur disappeared and was not consistently heard again until 6 weeks later. Polyarthritis vanished, and

the elevated erythrocyte sedimentation rate quickly returned to normal. During this period of treatment the only toxic effect of therapy noted was a mild moon facies.

One week afer the cessation of cortisone therapy another rebound occurred, characterized by polyarthritis, fever, an elevated erythrocyte sedimentation rate and a prolonged P-R interval. No further therapy was given, and all the symptoms and signs subsided spontaneously within 6 weeks. It was at this time that the apical systolic murmur reappeared.

Approximately 6 months after the onset of the first course of cortisone the patient was returned to duty. The erythrocyte sedimentation rate and the electrocardiogram remained normal. A medium-pitched, apical systolic murmur of moderate intensity heard in all positions persisted throughout the follow-up period.

Acute Rheumatic Fever Treated with ACTH

A white boy aged 17 years entered the hospital on May 2, 1951, complaining of pain and stiffness in both knees, shoulders, wrists and elbows of 3 days' duration. He also had noted precordial chest pain and feverishness for 6 days. The patient had had a sore throat 3 weeks prior to the onset of symptoms, but did not seek medical care. The past history revealed no evidence of rheumatic manifestations.

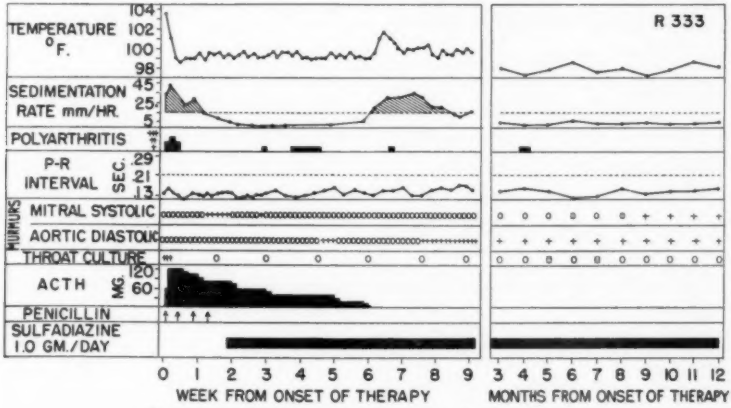

Fig. 96. Acute rheumatic fever treated with ACTH.

On admission the patient was found to have polyarthritis involving both knees, shoulders, elbows, hips and feet. The rectal temperature was elevated, as was the erythrocyte sedimentation rate. The electrocardiogram was normal. Examination of the heart revealed no murmurs or pericardial friction rub. A throat culture showed group A streptococci, type 1, and the antistreptolysin titer of the serum was 250 units.

On the sixth day of his illness ACTH* was administered every 6 hours. The total daily dosage is shown in Figure 96. Potassium chloride, 1 gm., was given 3 times each day. For the first 4 weeks of treatment the patient received a diet containing less than 2 gm. of sodium chloride per day. Procaine penicillin in oil, 600,000 units, was given in order to eradicate the streptococcal carrier state. After this the patient received sulfadiazine prophylaxis. He remained at bed rest for 9 weeks, and was then allowed gradually increasing activity.

By the second day of therapy the temperature returned to normal, and by the third day the pain and tenderness of the joints disappeared. The erythrocyte sedimenta-

* ACTHAR (ACTH) was kindly furnished by the Armour Laboratories, Chicago, Ill.

tion rate fell rapidly and was within the normal range by the eighth day of treatment. Mild polyarthralgia reappeared on the twentieth and on the twenty-sixth days, lasting one day and 6 days, respectively. A variable, soft, medium-pitched, apical systolic murmur was heard from the ninth to the twentieth day of treatment. There was a 17 pound gain in weight between the second and fifth weeks of treatment. Scrotal edema appeared at the end of the fifth week. The low salt diet, which had been discontinued at the end of the fourth week, was reinstituted with a resulting prompt loss of 11 pounds and a disappearance of the scrotal edema. During the period of maximum water retention a moderately intense, high-pitched, basal diastolic murmur was heard for the first time. This murmur appeared for only 3 days, and was not heard again for 3 weeks. Coincidental with this gain in weight there was a 5 per cent increase in the transverse diameter of the heart on the teleroentgenogram. Marked acne and moon facies appeared by the fourth week of treatment.

After the cessation of therapy the patient had fever and an elevated erythrocyte sedimentation rate. Joint pains were present only one day. The fever and elevated erythrocyte sedimentation rate returned to normal without further treatment. During the period of rebound the aortic diastolic murmur was again elicited.

Thirteen weeks after the onset of treatment the patient was returned to duty. During the follow-up period occasional polyarthralgia was noted, but at no time were any of the joints tender. Nine months after the start of therapy a medium-pitched, apical systolic murmur, heard in all positions, appeared and persisted. The aortic diastolic murmur remained unchanged.

Comment

Each of these 3 patients obtained relief from the symptoms of rheumatic fever by treatment with aspirin, cortisone or ACTH. In general,

TABLE 12. *Schedules of Treatment**

DRUG	DAILY DOSE	DAY OF TREATMENT
Aspirin	1 grain per pound†	1 and 2
	2/3 grain per pound	3 through 7
	1/2 grain per pound	8 through 42
Cortisone	300 mg.	1
	200 mg.	2 through 5
	100 mg.	6 through 21
	75 mg.	22 through 35
	50 mg.	36 through 42
ACTH	120 mg.	1 through 4
	100 mg.	5 through 7
	80 mg.	8 through 14
	60 mg.	15 through 21
	40 mg.	22 through 35
	20 mg.	36 through 42

* As proposed for Cooperative Rheumatic Fever Study, American Heart Association.
† No daily dose to exceed 150 grains.

from the total results it appears that aspirin is most effective in relieving fever and polyarthritis. The sedimentation rate returned to normal values most rapidly in those patients receiving ACTH therapy. The P-R interval returned to normal somewhat more rapidly after hormone therapy than

after treatment with aspirin. The schedule of therapy used in the present study is summarized in Table 12.

Since the primary concern of therapy is the prevention of carditis and valvular heart disease, it is of some interest that the 3 patients received treatment before the appearance of cardiac murmurs. In spite of such early therapy the subsequent appearance of signs of valvular heart disease was not prevented. Although experience has demonstrated that such poor results are common, the data presently available do not allow a final conclusion as to whether the hormones have any effect on the incidence of subsequent valvular heart disease. Until such evidence is available, therapy with cortisone for periods of six to nine weeks and with somewhat higher doses may be advisable.

PREVENTION OF RECURRENT ATTACKS OF RHEUMATIC FEVER

Once a patient acquires rheumatic fever, it is mandatory to prevent recurrences. The most effective method at present is to place the patient on continuous prophylaxis against streptococcal infections. Less effective, mainly because not all streptococcal infections are recognized, is treatment of an infection with penicillin.

Recently the Committee on Prevention of Rheumatic Fever of the American Heart Association summarized the problems of prophylaxis.[2] It is their recommendation that all persons who have had an attack of rheumatic fever should receive continuous prophylaxis until the age of eighteen. In adults such therapy should be given for at least five years. The prophylactic regimen should be instituted early during the actual attack of rheumatic fever. Sulfadiazine, in a daily dose of 0.5 to 1.0 gm., is recommended. Toxic reactions are usually minor and infrequent and usually develop during the first six to eight weeks of therapy. Sulfadiazine should be discontinued if leukopenia develops. For those patients who will not tolerate sulfadiazine, 50,000 to 100,000 units of oral penicillin should be administered twice daily before meals. It is possible that somewhat smaller doses of oral penicillin may be effective, but further study is required to determine the universal effective dose.

If streptococcal infections occur in the person who has had a previous attack of rheumatic fever or who has signs of valvular heart disease, every effort should be made to eradicate the streptococcus from the respiratory tract. Since the risk of rheumatic fever is greatly increased in this population group as compared to the normal population, it is recommended that 300,000 to 600,000 units of procaine penicillin G in oil containing 2 per cent aluminum monostearate be injected every *second* day. A total of four injections should be administered. It appears likely that a single injection of 600,000 to 900,000 units of Bicillin will be equally effective.

CONCLUSION

Today it is possible for the physician to prevent many initial attacks of rheumatic fever and most recurrent attacks of the disease by the proper use of the antibacterial drugs. Treatment of the acute attack of rheumatic fever is not altogether satisfactory. Aspirin, ACTH or cortisone controls the symptoms of rheumatic fever, but there is little evidence that these compounds prevent valvular heart disease. The training of the public by the physician in all aspects of streptococcal infections and rheumatic fever should result in a great decrease in the incidence of rheumatic valvular heart disease.

The authors are grateful to all members of the Streptococcal Disease Laboratory, and especially Drs. Harold B. Houser and Ernest J. Clark, for assistance in these studies.

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INDEX

Page numbers of clinic titles are given in **boldface** type.

Acetylcholine bromide in paroxysmal tachycardia, 225
ACTH in acute rheumatic fever, 271
Adams-Stokes attack, 233
Anemia, hypochromic, in differential diagnosis of rheumatic fever, 260
Anesthesia
  for cardiac surgery, **147–157**
  for surgical treatment of patent ductus arteriosus, 165
Aneurysm
  of aortic sinus, pathology, 19
  pulmonary, arteriovenous, diagnosis, 145
Angiocardiography, **73–92**
Angiogram, venous, technique, 74
Antistreptolysin O titer in diagnosis of rheumatic fever, 261
Aorta, ascending, atresia or marked hypoplasia, with or without mitral atresia or stenosis, diagnosis, 144
  coarctation, and patent ductus arteriosus, pathology, 17
    aortography in, 90
    catheterization in, 101
    diagnosis, 120, 174
      and management, **173–180**
    electrocardiogram in differential diagnosis, 65
    pathology, 16
Aortagram, technique, 75
Aortic arch, anomalies, and treatment, **181–195**
    diagnosis, 187
    prognosis, 191
Aortic septum, defect of, pathology, 17
Aortic sinus, aneurysm of, pathology, 19
Aortic valve, atresia, pathology, 40
  murmurs, 9
  stenosis, diagnosis, 122
    pathology, 19
Aorticopulmonary fistula, pathology, 17
Aortography, 88
Arrhythmias, cardiac, **215–234**
  complicating cardiac surgery, 153
  in diagnosis of rheumatic fever, 257
Artery, coronary, anomalous origin from pulmonary artery, diagnosis, 124
  left, aberrant, originating from pulmonary artery, 236, 237
    anomalous origin, electrocardiographic patterns, 61, 62
      from pulmonary trunk, pathology, 21
Aspirin in acute rheumatic fever, 269
Ataxia, Friedreich's, 260
Atrial septum, defect of, and intact ventricular septum, with pulmonary valvular stenosis, pathology, 33
  and mitral stenosis, pathology, 27
  diagnosis, 124
  lower, defect of, and deformity of atrioventricular valves, pathology, 28
Atrioventricular canal, common, persistent, pathology, 28
Atrioventricular valves, deformity of, and defect of lower atrial septum, pathology, 28
Atrioventricularis communis, angiocardiography in, 86
Atrium, left, anomalous connection with persistent left superior vena cava, pathology, 48
  communication with coronary sinus, pathology, 29
Auricle, left, enlargement of, fluoroscopic and roentgenographic findings, 137
  right, enlargement of, fluoroscopic and roentgenographic findings, 136

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ACETYLCHOLINE bromide in paroxysmal tachycardia, 225
ACTH in acute rheumatic fever, 271
Adams-Stokes attack, 233
Anemia, hypochromic, in differential diagnosis of rheumatic fever, 260
Anesthesia
  for cardiac surgery, **147–157**
  for surgical treatment of patent ductus arteriosus, 165
Aneurysm
  of aortic sinus, pathology, 19
  pulmonary, arteriovenous, diagnosis, 145
Angiocardiography, **73–92**
Angiogram, venous, technique, 74
Antistreptolysin O titer in diagnosis of rheumatic fever, 261
Aorta, ascending, atresia or marked hypoplasia, with or without mitral atresia or stenosis, diagnosis, 144
  coarctation, and patent ductus arteriosus, pathology, 17
    aortography in, 90
    catheterization in, 101
    diagnosis, 120, 174
      and management, **173–180**
    electrocardiogram in differential diagnosis, 65
    pathology, 16
Aortagram, technique, 75
Aortic arch, anomalies, and treatment, **181–195**
    diagnosis, 187
    prognosis, 191
Aortic septum, defect of, pathology, 17
Aortic sinus, aneurysm of, pathology, 19
Aortic valve, atresia, pathology, 40
    murmurs, 9
    stenosis, diagnosis, 122
      pathology, 19
Aorticopulmonary fistula, pathology, 17
Aortography, 88
Arrhythmias, cardiac, **215–234**
    complicating cardiac surgery, 153
    in diagnosis of rheumatic fever, 257
Artery, coronary, anomalous origin from pulmonary artery, diagnosis, 124
    left, aberrant, originating from pulmonary artery, 236, 237
      anomalous origin, electrocardiographic patterns, 61, 62
        from pulmonary trunk, pathology, 21
Aspirin in acute rheumatic fever, 269
Ataxia, Friedreich's, 260
Atrial septum, defect of, and intact ventricular septum, with pulmonary valvular stenosis, pathology, 33
    and mitral stenosis, pathology, 27
    diagnosis, 124
  lower, defect of, and deformity of atrioventricular valves, pathology, 28
Atrioventricular canal, common, persistent, pathology, 28
Atrioventricular valves, deformity of, and defect of lower atrial septum, pathology, 28
Atrioventricularis communis, angiocardiography in, 86
Atrium, left, anomalous connection with persistent left superior vena cava, pathology, 48
    communication with coronary sinus, pathology, 29
Auricle, left, enlargement of, fluoroscopic and roentgenographic findings, 137
  right, enlargement of, fluoroscopic and roentgenographic findings, 136

Auricular fibrillation, 219
Auricular flutter, 219, 222
Auricular septum, defects of, angiocardiography in, 88
murmurs, 11
Auriculoventricular dissociation without block, 218
Auscultation in diagnosis of heart disease, 8

Bicillin in recurrent rheumatic fever, prophylactic, 273
Blood flow, venous, pulmonary, impaired, pathology, 22
Blood sedimentation rate in diagnosis of rheumatic fever, 260
Blood vessels, transposition, angiocardiography in, 81
complete, diagnosis, 141
pathology, 42
surgical treatment, 210
Bradycardia, sinus, 215, 218

Cardiovascular anomalies, congenital, cyanotic, surgical treatment, **197–213**
with decreased pulmonary blood flow, 200
with normal or increased pulmonary blood flow, 210
Catheterization, cardiac, clinical, **93–113**
Chest. See *Thorax*.
Chorea, fidgets and tics, 259
Sydenham's, 259
Coarctation of aorta. See under *Aorta*.
Cooling of body for cardiac surgery, 154
Cor biloculare, pathology, 38
Cor triatriatum, pathology, 27
Cor triloculare biatriatum, pathology, 38
Cortisone in acute rheumatic fever, 269
Cyanosis, in diagnosis of heart disease, 4, 6
of cardiac origin, 132
persistent, in congenital heart disease, pathology, 32
with absent right ventricle or no right ventricular hypertrophy, 46

Diagnosis
and management of coarctation of aorta, **173–180**
clinical, of cyanotic congenital malformations of heart, **131–146**
of congenital cardiovascular malformations unaccompanied by cyanosis, **115–130**
Digifolin in supraventricular paroxysmal tachycardia, 225
Digitoxin in supraventricular paroxysmal tachycardia, 225
Ductus arteriosus, patent, and coarctation of aorta, pathology, 17
angiocardiography in, 86
aortography in, 88
cardiac catheterization in, 99
Ductus arteriosus, patent, diagnosis, **116, 159**
murmurs, 10
pathology, 17
treatment, surgical, **159–171**
with pulmonary hypertension, pathology, **39**

Ears, eyes and hands in diagnosis of heart disease, **3–12**
Ebstein's disease, angiocardiography in, **85**
with interauricular communication (cyanotic type), diagnosis, 140
Ebstein's malformation of tricuspid valve, pathology, 46
Eisenmenger complex, angiocardiography in, **87**
diagnosis, 142
pathology, 36
surgical treatment, 212
Electrocardiogram
in congenital malformations of heart, **51–71**
in diagnosis of cyanotic congenital cardiac malformations, 137
in differential diagnosis of congenital heart disease, 64
normal, 52
Erythema annulare in rheumatic fever, 6, 251
Examination, physical, in diagnosis of heart disease, 5
Extrasystoles, 258
Eyes, hands and ears in diagnosis of heart disease, **3–12**

Fallot, tetralogy of, angiocardiography in, 78
cardiac catheterization in, 103
diagnosis, 138
pathology, 34
surgical treatment, 204
Fever in diagnosis of rheumatic fever, 253
Fibroelastosis, congenital, electrocardiographic patterns, 63
endocardial, 22, 243
pathology, 244
symptoms, signs, and laboratory findings, 244
treatment, 244
endomyocardial, 22
Fidgets, tics and chorea, 259
Fistula, arteriovenous, pulmonary, pathology, 49
Foramen ovale, premature closure, pathology, 30
patent, with pulmonary valvular stenosis, angiocardiography in, 80
Friction rub. See under *Heart*.
Friedreich's ataxia, 260

Glycogen storage disease, 239
diagnosis, 124
electrocardiographic patterns, 62
treatment, 242

Habit spasms, 260
Hands, ears and eyes in diagnosis of heart disease, **3–12**
Heart, anomalies explored, 148
block, 231
auriculoventricular, 231
congenital, 232
sino-auricular, 231
disease, acyanotic, pathology, 14
clinical studies, value of, 12
congenital, pathology, **13–49**
cyanotic, persistent, pathology, 32
with decreased pulmonary markings, electrocardiogram in differential diagnosis, 66
diagnosis, eyes, hands and ears in, **3–12**
fluoroscopic and roentgenographic examinations, 135
friction rub, 10
hypertrophy, 134
diagnosis, 12
electrocardiographic patterns, 60
idiopathic, electrocardiographic patterns, 59
in infancy, **235–250**
malformations, congenital, cyanotic forms associated with right ventricular hypertrophy, pathology, 33
electrocardiogram in, **51–71**
murmurs, 8
congenital, 10
functional, 254
in diagnosis of rheumatic fever, 254
organic, 256
significance, 134
position, anomalies of, electrocardiographic patterns, 68
strain, combined, electrocardiographic patterns, 63
electrocardiographic patterns, adaptation, type, 52, 55
barrage type, 52, 55, 57
surcharge type, 52, 56
left, electrocardiographic patterns, 59
right, electrocardiographic patterns, 52
vascular markings, 135
History in diagnosis of heart disease, 3
Hypertension, pulmonary, secondary to increased pulmonary flow, diagnosis, 129
with patent ductus arteriosus, pathology, 39
Hypertrophy, ventricular, right, absent, with cyanosis, 46

Infundibular stenosis, punch valvulotomy for, 208
Inspection in diagnosis of heart disease, 5

Joint pains in diagnosis of heart disease, 5

Leukocytosis in diagnosis of rheumatic fever, 260
Lutembacher syndrome, 27, 28

Malformations, cardiovascular, congenital, acyanotic, diagnosis, **115–130**
cyanotic, diagnosis, **131–146**
Mitral valve, accessory tissue, pathology, 25
atresia, pathology, 40
diastolic rumble, 9
insufficiency, pathology, 24
murmurs, 8
presystolic, 9
systolic, 9
stenosis, and atrial septal defect, pathology, 27
pathology, 25
Morphine sulfate, preoperative use in cardiac surgery, 151
Murmurs, cardiac. See under *Heart*.
Myocarditis, 245
isolated, diagnosis, 124
pathology, 246
symptoms, signs and laboratory findings, 246
treatment, 247

Nodules, rheumatic, in rheumatic fever, 252

Ostium, infundibular, stenosis of, pathology, 31

P wave contour in congenital heart disease, 63
Pacemaker, wandering, 215, 218
Pains, joint, in diagnosis of heart disease, 5
leg, in diagnosis of rheumatic fever, 253
Palpation in diagnosis of heart disease, 6
Pathology, functional, of congenital cardiac disease, **13–49**
Penicillin in recurrent rheumatic fever, prophylactic, 273
Percussion in diagnosis of heart disease, 7
Pericardial cavity, exploration, 199
Pericardium, defects of, pathology, 30

Pleural cavity, exploration, 199
Precordial distress, 258
Premedication for cardiac surgery, 149
Prostigmin in paroxysmal tachycardia, 227
Pseudotruncus communis, diagnosis, 140
Pulmonary valve, atresia, with intact ventricular septum, pathology, 42
stenosis, cardiac catheterization in, 104
diagnosis, 128
isolated, pathology, 30
murmurs, 11
pure, angiocardiography in, 87
syndromes resulting from, 105
with cyanosis, surgical treatment, 200
with intact ventricular septum and atrial septal defect, pathology, 33
with interauricular communication, diagnosis, 139
with patent foramen ovale, angiocardiography in, 80
with poststenotic dilatation of pulmonary artery, interatrial septal defect and infundibular valvelike stenosis, surgical treatment, 204
with reopening of foramen ovale or atrial septal defects, surgical treatment, 200
Punch valvulotomy for infundibular stenosis, 208

QUINIDINE in supraventricular paroxysmal tachycardia, prophylactic, 227
Quinidine sulfate in ventricular paroxysmal tachycardia, 227, 228

RESPIRATION, labored, in diagnosis of heart disease, 4
Rhabdomyoma, congenital, 242
electrocardiographic patterns, 63
Rheumatic fever, acute, treatment, 268
diagnosis, **251–263**
recurrent, prevention of, 273
treatment and prevention, **265–274**

SCLEROSIS, endocardial, diagnosis, 122
pathology, 22
Scopolamine hydrobromide, preoperative use in cardiac surgery, 151
Septal defects, electrocardiogram in differential diagnosis, 65
Shunt operations
for cardiovascular anomalies, 208
for tetralogy of Fallot, 204
Sinus, coronary, communication with left atrium, pathology, 29
Sinus arrhythmia, 215, 218
Sinus bradycardia, 215, 218
Sinus tachycardia, 215, 218, 257
Spasms, habit, 260
Spells in diagnosis of heart disease, 4
Subaortic valve, stenosis, diagnosis, 122
pathology, 19
Sulfadiazine in recurrent rheumatic fever, prophylactic, 273
Surgery, cardiac, anesthesia for, **147–157**
postoperative care and complications, 155
preoperative preparation, 149
Sydenham's chorea, 259
Syndrome, Lutembacher, 27, 28
Systoles, premature, 219

TACHYCARDIA, paroxysmal, 222, 258
in young infants, 228
repetitive, 229
treatment, 225
sinus, 215, 218, 257
Taussig-Bing complex, pathology, 39
Taussig-Bing heart, angiocardiography in, 82
diagnosis, 143
Taussig-Bing syndrome, surgical treatment, 212
Tetralogy of Fallot. See under *Fallot*.
Thorax, drainage, 199
Thrill in diagnosis of heart disease, 7
Throat, sore, in diagnosis of heart disease, 5
Tics, 260
chorea and fidgets, 259
Tricuspid valve, atresia, angiocardiography in, 83
diagnosis, 139
pathology, 46
surgical treatment, 207
with complete transposition of great vessels, diagnosis, 143
Ebstein's malformation, pathology, 46
murmurs, 9
stenosis, diagnosis, 139
with complete transposition of great vessels, diagnosis, 143
Truncus arteriosus communis, diagnosis, 142
persistent, angiocardiography in, 85
pathology, 37
surgical treatment, 212

VALVULOTOMY
for pulmonary valvular stenosis, 201
for tetralogy of Fallot, 207
punch, for infundibular stenosis, 208
Vascular ring, 183
Veins, pulmonary, anomalous entrance into right auricle, venae cavae or coronary sinus, diagnosis, 144
partial anomalous connection, pathology, 29
partial anomalous drainage, diagnosis, 127
total anomalous connection, pathology, 44

Vena cava, superior, left, persistent, anomalous connection with left atrium, pathology, 48
Ventricle(s), common ejectile force for systemic and pulmonary circulations, pathology, 33
left, failure of, pathology, 14
hypertrophy of, electrocardiographic patterns, 137
fluoroscopic and roentgenographic findings, 136
increased work of, conditions causing, 116
right, absent, with cyanosis, pathology, 46
hypertrophy, electrocardiographic patterns, 138
fluoroscopic and roentgenographic findings, 135
increased work of, conditions causing, 124
nonfunctioning, surgical treatment, 207
Ventricle(s), single, angiocardiography in, 84
with hypoplastic pulmonary artery, diagnosis, 141
with normal-sized or dilated pulmonary artery, diagnosis, 144
without pulmonary stenosis, surgical treatment, 213
Ventricular septum, defect of, angiocardiography in, 87
diagnosis, 119
in muscular portion, diagnosis, 127
pathology, 14
intact, and atrial septal defect, with pulmonary valvular stenosis, pathology, 33
with pulmonary valvular atresia, pathology, 42
murmurs, 10

WILSON phenomenon, 52
Wolff-Parkinson-White syndrome, 230